Bachelor's Thesis

Bachelor's Degree in Industrial Technology Engineering

Engineering Study on the Static Resistance of the Tutankhamun Class Chariot

Report

Author: Sandra Castany

Directors: Lluís Roger Casals
Carles Puig Pla

Call: September 2018

Escola Tècnica Superior
d'Enginyeria Industrial de Barcelona

Summary

This thesis report presents an engineering study on the static resistance of the Tutankhamun's class chariot. It includes a 3D modelling of the chariot and analyses of the different parts.

Section 5 provides a brief historical introduction to Egyptian culture and religion which is fundamental to understand the importance of the war chariot, not just as a weapon but as a sign of the Pharaoh's and the nation's power. It also includes an introduction to chariots in history and the birth of the Egyptian chariot and its importance in war and war tactics.

Section 6 provides the description of the Tutankhamun's class chariot and its parts separately and the materials used in their construction. The visit to the Grand Egyptian Museum Conservation Center is explained in detail.

Section7 is dedicated to the mechanical analyses of the chariot. This chapter provides information about the mechanical properties of wood, particularly elm wood, and some of the equations used for the resistance and deformation analyses.

Section 8 explains the finite element method is explained, and the 3D modelling of the chariot is presented along with relevant measurements used in to perform the analyses.

Section 9 includes the analyses of the different parts of the chariots regarding their deformation and resistance. The chariot's rollover stability is calculated in Section 10.

Table of Contents

1. Glossary of Terms

1.1. Glossary of Technical Terms

Axle: The pin, bar, shaft, or the like, on which or by means of which a wheel or pair of wheels rotates. In the case of the Egyptian chariots, it was positioned underneath the floor frame in the rear part.

Body: Describes a part of the structure of the chariot. It refers to the floor frame and the siding frames of the chariot.

Felloe: The circular rim, or a part of the rim of a wheel, into which the outer ends of the spokes are inserted and mortised.

Linch pin: A toggle pin passing through the end of the axle to prevent the wheels from slipping off.

Nave (hub): Central part of the wheels through which the axle passes.

Pole: It is used to describe the long piece of wood that connected the body and axle of the chariot with the yoke.

Spoke: One of the bars radiating from the hub or nave of a wheel and supporting the rim or felloe.

Tyre: Outer element of the wheels that protects the felloe. In Antiquity it was made of wood or metal.

Wheel track: Distance between the centres of the treads of the two wheels.

Yoke: A device for joining together a pair of animals that pull a plow, wagon, etc., usually made of a wooden bar set across the animals, with two bow-shaped pieces, each enclosing the head of one of the animals.

1.2. Glossary of Abbreviations

μ: Frictional coefficient between wood and sand.

a: Acceleration of the horses when they start to pull the chariot.

A: Section

a_N: Normal acceleration.

E: Young's Modulus.

e: Width of the wheel felloe.

f: Frictional coefficient between greased parts made of wood.

F_f: Friction.

F_h: Force of the pull of the horses.

F_p: Pull of one charioteer.

G: Shear modulus or Modulus of Rigidity.

g: Gravity.

H: Height of a person.

I: Moment of inertia.

m: Weight per person.

M: Weight of the chariot.

N: Normal force produced by the contact between the wheel and the floor.

N_h: Normal force produced by the contact between the horses and the yoke.

P: Load due to the weight of the two charioteers.

P_{body}: Weight of the body of the chariot.

R: Reaction force due to the weight of the charioteers and the cabin to the axle.

R_p: Reaction force due to the weight of the charioteers and the cabin to the pole.

v_m: Medium speed.

v_{max}: Maximum speed.

δ: Displacement

ν: Poisson's ratio.

ρ: Density.

σ: Uniaxial normal stress.

σ_e: Yield Stress.

σ_{VM}: Equivalent Von Mises stress.

τ: Shear stress.

2. List of Figures, Tables and Graphics

2.1. List of Figures

2.2. List of Tables

2.3. List of Equations

3. Preface

3.1. Motivation and Origin of the Project

The idea of this project came from my love for history, archaeology and Ancient cultures. When I was a kid my mother used to explain to me the history of Ancient cultures, their science and religion and the technology they had developed. I was fascinated by the developments and this fascination did not fade when I grew up.

When choosing a career path, you usually set aside the deep study of other interests you may have. In technological degrees we often forget that technology, science and culture have always walked together. It is true that, for society to progress, science and technology are vital. However, without the needs of the people, technology would have no reason to exist. And these needs are constantly changing and evolving, just as humanity does.

This project originated when I remembered a visit to the Egyptian Museum in Cairo. The guide made us notice the chariots standing inside the cabinets were not as simple as they seemed. This came to my mind while studying an optional subject about Ancient Egypt in the ETSEIB. I started looking for more information and realized that it could be an interesting project, one that did not have many precedents. I contacted an engineer professor emeritus from Wisconsin University, professor Bela I. Sandor, who was kind enough to help me and give me information about the chariots. After speaking with different teachers, I decided to continue with this project which combines two of my passions: archaeology and engineering.

4. Introduction

The aim of this project is to study the Tutankhamun's class chariot from an engineering point of view. The idea surged from a previous visit to Cairo where a guide explained the importance of the chariot in ancient Egyptian culture.

4.1. Objectives of the Project

The main objective of this project is to prove the high technology design of the Tutankhamun class chariot and to study its static performance and resistance, not only as a hole but of the different parts separately.

This project intends to prove the high technology used in the modelling of the Egyptian chariot. Other more specific objectives to have in mind to achieve the main goal are the study of the building of the chariot, the modelling of a 3D structure of the chariot close enough to reality to perform the analyses, the implementation of this model into a finite element program and the verification of the resistance of the chariot.

4.2. Scope of the Project

The research of this project consists on the lecture of several articles and books regarding chariots through history and more specifically, Egyptian chariots. This research is needed to understand how Tutankhamun class chariots were built and the importance of such an innovative design in that time. Understanding the building of the chariot is essential to be able to recreate the different parts of the chariot and their unions in the 3D model.

The 3D model has been created with SolidWorks which is a solid modeler and utilizes a parametric feature-based approach to create models and assemblies and CATIA which is another software for computer-aided design.

The static simulations have been performed with Ansys, which is a finite element method software. It is a powerful and versatile tool that allows the study of complex situations and geometries.

There are limitations to this project. Due to the lack of knowledge and resources, a more realistic implementation of the unions between parts could not be performed. This project does not contemplate the dynamics of the chariot due to the lack of knowledge, time and resources. However, it pretends to be the preface of a master thesis that will include the dynamics of the chariot regarding turns, rollovers and accelerations of the chariots and an orthotropic analysis of the chariot.

5. Historical Contextualization

5.1. Introduction

Currently, society changes and develops constantly, there seems to be a cult of immediate solutions, it seems the dictatorship of science and technology over other cultural values inherent to humanity itself and to our time. Culture seems to be absolutely conditioned by science and technology. Especially in modern Western culture, the arts and history seem to have taken a second place in the global development.

However, many times, specialists forget technology is a consequence of the demand of a society and the time it lives. Therefore, the study of a culture cannot be restricted only to technology. In every technological fact there are important cultural variables that should not be ignored. A technological fact cannot be understood without its ideological and cultural environment. Just like a literary movement cannot be understood outside of its cultural context.

This is especially relevant in the study of ancient cultures, where archaeologists must interpret and comprehend that culture through the current perspective. The modern world has lost the Renaissance spirit, missing a global view of the world, in favor of specialization which increasingly minimizes the area of study. This favors that many disciplines ignore each other in the study of the ancient cultures. It should not be forgotten Leonardo da Vinci studied hydraulics to be able to draw women's hair in a more realistic way or history of art cannot be studied without having knowledge of religion.

When studying ancient cultures, it is essential not to adopt a modern approach to the subject. It is important to understand the culture, society and religion of the time to be able to understand their progress through the reconstruction of archeological rests and their subsequent analysis. For this reason, it is important for this project to have a historical introduction to ancient Egyptians' culture, to understand the function and importance their chariots had at the time.

5.2. The Egyptian Civilization: Fundamental Socioeconomic Aspects

With more than 3000 years, Ancient Egypt's history is the longest and most documented of the world. Herodotus (*c*.484-*c*.425 BC) with *The Histories*[1] and Manetho (3rd century BC) with his work

[1] Herodotus wrote *The Histories* in 440 BC and serves as a record of the ancient traditions, politics, geography, and clashes of various cultures that were known in Western Asia, Northern Africa and Greece at that time.

Aegyptiaca [2] were the main sources of information on Pharaonic culture until the 18th and 19th centuries, when explorers and archaeologists began to arrive in Egypt.

5.2.1. Geographic Situation and Environmental Conditions

In the formation of a civilization like the Egyptian, which is one of the most brilliant of the antiquity, several factors converge. These factors have their roots mostly in the climatic and environmental conditions that influenced the ways of life and determined their spiritual, artistic and technological evolution.

Figure 5.2.1. *Ancient Egypt Map*

It is often said that most of peculiarities, ways, habits and character of a nation are attributable to the physical characteristics of a country. Rousseau stated in *The Social Contract* (1762) that "despotism is suitable to hot countries, barbarism to cold ones, and good polity to temperate regions"[3]. It referred to a geographical determinism that, according to Rousseau, would have explained Pharaonic despotism. Egyptian history has been mostly determined by its geographical configuration. As seen in Figure 5.2.1, Egypt is constituted mainly by the Nile Valley. To the North, the area of the Nile Delta (Lower Egypt) is characterized by the wide and fertile plains. To the South (Upper Egypt), the area of the Nile Valley is formed by a narrow strip of land next to the wing of the river surrounded by desert.

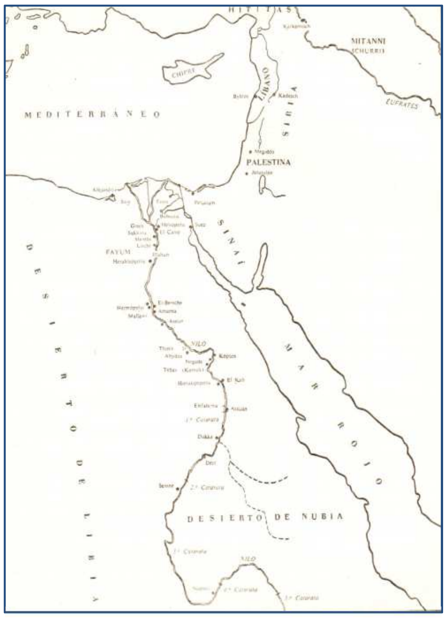

Figure 5.2.2. *Egypt and bordering countries*

The same natural unity of its territory was, without a doubt, the cause of which it could accomplish its national unit before any other nation.

Nile Valley's fertility determined a quick settlement of tribes, given their dependence on the great river as the only source of prosperity. This meant relations between riparian populations started to develop, forming a civilization that little by little imposed to other peoples and that expressed itself in the same language and the same religion.

[2] Manetho wrote the *Aegyptiaca* (3rd century BC). It was organized chronologically and divided into three books. The division of rulers into dynasties was an innovation.

[3] Rousseau, J.-J. (1762). *The Social Contract* (Vol. 3). Amsterdam. P. 41

It is also important to understand that the reason why Egypt was a stable nation over millennia was because it is a unit clearly delimited by nature. Therefore, it was easily defensible against foreign enemies (Figure 5.2.2).

To the South, Egypt only links to Nubia through a narrow valley of difficult access. To the East there is only a small path through a desert area that links Egypt to Syria. These routes were crossed over millennia by nomads drawn by the wealth of Egypt. To the West, the Delta is extended to a semi-desert area beyond which there have never been large human settlements. To the North, the Delta, through which they had a wide access to the sea for many months of the year by the seven branches of the Nile. On the contrary, the marshes created by alluviums of the great river made it inaccessible from the outside. The eastern Mediterranean is one of the best seas in the World for navigation. The Egyptians, from the Nile Delta, bordered the coasts with their boats and could safely reach the beaches of Syria, Cyprus and Crete (Minoan civilization), the islands of the Aegean Sea, Asia Minor and Greece, promoting like this an intense commercial and cultural exchange between different peoples.

The natural resources of the country facilitated its rapid development. The annual rise of the level of the river and the deposited alluviums ensured abundant harvests and, therefore, the welfare of the population.

The almost total lack of rain made life depend, almost exclusively, on the Nile floods. To obtain a maximum use of the water, they scored the ground, being able to irrigate lands that were not reached by the flood. They built bombs for overflows and invented instruments like the Nilometer (Figure 5.2.3) to measure and try to predict the floods of the river.

Figure 5.2.3. *Nilometer (Rhoda Island)*

This led to the emergence of hydraulic societies where the "State" appears in arid regions to control, plan and exploit water resources. The result was a bureaucratized society with the existence of a central power that regulated the production and distribution of products. This period corresponds to the Predynastic, Protodynastic and Archaic period. It is the most unknown period in which the population gathered in "cities" such as Sais, producing the appearance of the first kingdoms of the Lower and the Upper Egypt. Menes or Narmer was the first pharaoh who unified the two kingdoms creating a state structure that lasted almost the entire history of Egypt.

The Ancient Egypt society was based on agriculture and livestock (agricultural society). The utilization of bronze (alloy consisting mainly on copper and tin) would not appear until the Middle Kingdom (2134-1690 BC) and it was perfected until reaching the New Kingdom (1549-1069 BC).

5.2.2. Political and Ethnic Divisions of the Territory

Despite the great importance of the Nile, which crosses the entire territory from North to South, there was a rigid separation of both territories that is expressed graphically in the expression "The two countries, Upper and Lower Egypt". Both lands had their own heraldic plant (the reed and the papyrus, respectively) and their own representative gods (Seth and Horus, respectively).

The different evolution of the two lands is due to geographical and ethnic characteristics (Figure 5.2.4). The nomads from Upper Egypt (6th and 5th millennia BC) belonged to the African Canaanite tribe, whereas the population from Lower Egypt was more heterogeneous and probably came from Syria and Palestine. In addition, Upper and Lower Egypt were clearly differentiated in their geographical aspect. This factor, added to the ethnic differences of both kingdoms, caused that the life of the inhabitants of the two lands developed under very different conditions, creating two clearly differentiated lifestyles: The Lower Egypt, especially the Nile Delta, remained open to foreign influences throughout time (more cultural and commercial exchange). On the other hand, Upper Egypt was hardly affected by external influences. Considering the conservative character of Ancient Egyptians, this explains the leading role of Upper Egypt, both in the political and cultural aspect of Egypt, because their traditions and culture would have remained untouched.

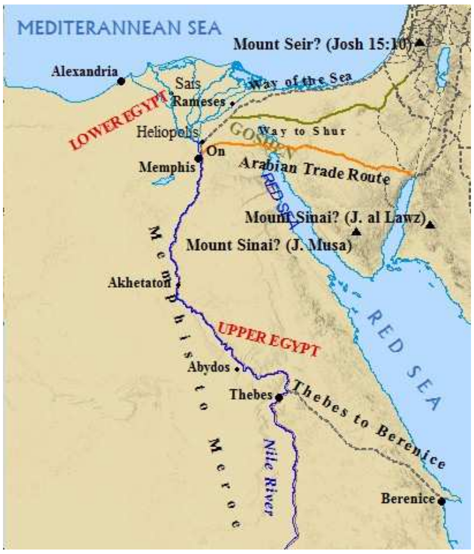

Figure 5.2.4. *Upper and Lower Egypt*

The monarch, who reigned over the two lands, always wore and was represented with the double Egyptian crown, composed by the crown of Upper Egypt and the crown of Lower Egypt (Figure 5.2.5).

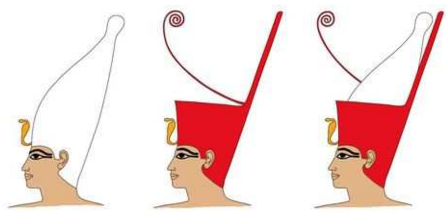

Figure 5.2.5. *White Crown (Upper Egypt), Red Crown (Lower Egypt), Double Crown (Unified Egypt)*

Administratively, Egypt was divided into *nomes*. *Nomes* were territorial divisions that owned their own capital and worshiped their own gods. Upper Egypt was divided into 22 *nomes*, whereas Lower Egypt was divided into 20 *nomes*.

Egypt's history divided in 31 Royal Dynasties, organized by Manetho, continues to be a reference between the Egyptologists, who grouped them into different periods.

3050 to 2686 BC Early Dynastic Period (1st and 2nd Dynasties)

2686 to 2181 BC Old Kingdom (3rd to 6th Dynasties)

2181 to 1991 BC First Intermediate Period (7th to 11th Dynasties)

2134 to 1690 BC Middle Kingdom of Egypt (11th to 12th Dynasties)

1674 to 1549 BC Second Intermediate Period (13th to 18th Dynasties)

1549 to 1069 BC New Kingdom of Egypt (18th to 20th Dynasties)

1069 to 653 BC Third Intermediate Period (21st to 24th Dynasties)

672 to 332 BC Late Period of Ancient Egypt (25th to 30th Dynasties)

332 BC to 641 AD Greco-Roman Era

Protodynastic Period, where Dynasty 0 appeared, must also be mentioned. It is the most unknown Period and covers approximately a fourth of a millennium. This prehistoric process, that occurred in the Neolithic period lead off the first settlements and agriculture.

Some of the main characteristics of the different periods of the Ancient Egypt are indicated below:

- *Old Kingdom*: It was the time of consolidation of the first State and the time when the first pyramids were built, Djoser, Khufu, Khafra and Menkaure.
- *First Intermediate Period*: Pharaoh's power weakened in favor of local leaders which lead to internal divisions.
- *Middle Kingdom of Egypt*: Egypt's unit and the Pharaoh's power return.
- *Second Intermediate Period*: The Hyksos, coming from the Near East, dominated the majority of Egypt taking advantage of the internal divisions and the lack of a single powerful Pharaoh. They imported the horse and the battle chariot, being its use in the invasion a key factor for its success.
- *New Kingdom of Egypt*: Egypt reunifies and strengthens. This is the time of Pharaohs like Ramses II.
- *Third Intermediate Period*: It was a period of decline and political instability. It coincided with the Late Bronze Age and was followed by the Late Period. Again, the internal divisions weaken Egypt that suffers the Assyrian and Persian invasions and finally Alexander the Great's conquest.
- *Greco-Roman Era*: Egypt becomes a Roman province in 30 BC and its identity finally blurs.

During the middle Ages, no one was able to read the hieroglyphic writing and Egypt's history remained forgotten until Champollion's arrival who, in the 19th century, managed to decipher the hieroglyphic writing thanks to the discovery of the Rosetta stone. He is considered the father of Egyptology.

5.2.3. The Ancient Egyptian Religion

Religion in Ancient Egypt played a decisive role. Faith in the gods and religion inspired the whole conception of the world, moral, artistic manifestations, etc.

Ancient Egyptians were polytheistic and their explanation of the world (cosmology) was produced through myth (mythical societies). They attributed nature with a magical power. They worshiped divinities that were closely related to nature (they were represented, in many occasions, with the head of an animal and human body, as shown in Figure 5.2.6) and with the great cosmic phenomena (like the Nile floods, the sunrise or the moonrise, etc.). Unlike modern man, the Ancient Egyptian integrated nature into his daily life and considered himself part of it. The Pharaoh was the only member of society who was considered of divine origin. He was the embodiment of an idea the community used to escape chaos (the unforeseen, the new).

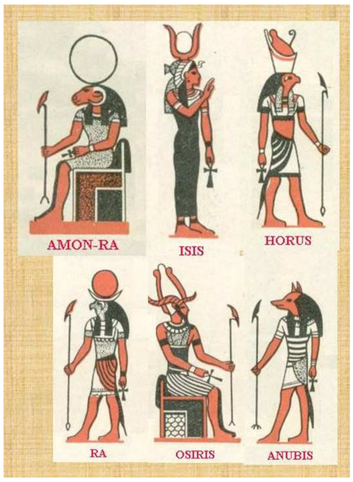

Figure 5.2.6. *Some of the most important Egyptian deities were Amon-Ra, Isis, Horus, Ra, Osiris or Anubis.*

There was a powerful caste of priests, emerged under the protection of the great temples of great cities such as Memphis or Heliopolis. In the whole history of Ancient Egypt, 3000 years, there was the belief in an afterlife. In fact, their concern in the beyond made them dedicate a large part of their thoughts and activities to the construction of temples and monuments that extolled their gods. Populations, cities and palaces built with ephemeral materials have disappeared. However, the funerary temples of the pharaohs, built in stone (considered to be everlasting and eternal by the ancient Egyptians), still bear testimony of the hope in eternal life. So much so that almost everything that is known about the Egyptians, it has been deduced from images and scenes of their funeral temples.

5.2.4. Cultural and Scientific Achievements

According to Nietzsche, in *The Birth of Tragedy* (1872) "It's likely that almost everyone in a strict test would feel himself so thoroughly corrupted by the critical-historical spirit of our culture that he could make the previous existence of the myth credible only with something scholarly, by compromising with some abstractions. However, without myth that culture forfeits its healthy creative natural power: only a horizon reorganized through myth completes the unity of an entire cultural movement"[4].

The importance of the Egyptian culture within the history of humanity resulted in significant contributions in different areas such as art, architecture, engineering, medicine and science. Egypt made important contributions and established solid bases in each of those fields.

Although ancient Egypt was a mythical society, there are abundant interesting technological examples. Whether mythical or logical, a society confronts the medium that surrounds it through technology and the world is interpreted and assimilated from its own cultural perspective. A technology must be accepted and admitted by a society to be able to appear in it.

Science in ancient Egypt had a great prestige. Mixed with magical practices, there was a high level of knowledge. Bellow their main contributions are briefly introduced.

5.2.4.1. Writing

They had a complex writing system, based on semantic and phonetic signs, around 3000 BC. First, it was based on signs and representations of ideas that were of difficult use. This was the reason why there was a change towards hieratic writing (more simplified), which was only known by priests, with representation of sounds and consonants and not of ideas. Later, the demotic writing of phonetic characteristics was developed, and it was used by scribes.[5]

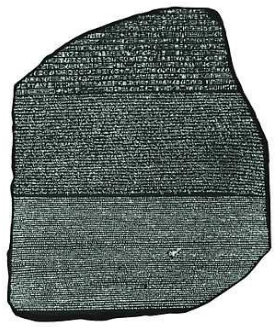

Figure 5.2.7. *The Rosetta Stone was found in the village of Rosetta (Rashid)*

They decomposed their language in a spelling book with an "alphabetical" order. The ability to read and write was the basis of social organization. They also developed a kind of a postal service, resembling the one used nowadays.

[4] Nietzsche, F. (1872). *The Birth of Tragedy*. E. W. Fritzsch. P. 61

[5] The scribes were civil servants of ancient Egypt that received lessons of calculation and writing and who also registered the Nile level by means of the *Nilometer*.

This writing was deciphered by Jean-François Champollion (1790-1832) thanks to the discovery of the Rosetta Stone (British Museum). This stone (in Figure 5.2.7) is a slab of black basalt found in 1799 near the village of Rosetta (Rashid) during the occupation of Egypt by Napoleon. It is a fragment of stele dated in the year 196 BC in which three different inscriptions appear. The first 14 lines are hieroglyphic characters[6], the 32 central lines are in demotic writing[7] and the remaining 54 lines are in Greek.

Champollion is considered the father of modern Egyptology since he deciphered their alphabet. He asserted that the phonetic alphabet was the model on which the alphabets of Western Asian nations were based especially the Hebrew, the Chaldean and the Syrian.

The Egyptian government had ministers and administrators with an efficient organization in all aspects. Curiously, what has been qualified as the first strike in history took place in Egypt around the 12th century BC, when workers demanded an improvement from Ramses III.

5.2.4.2. Hydraulic Technology

Some of their advances were vital for agriculture, which was the base of the economy (agricultural society). They invented the hoe and the plough, which appeared in pictographic representations such as the one seen in Figure 5.2.8. In addition, thanks to a mechanism called *shadoof* [8], they brought water from the Nile River to the canals, which helped irrigation. These canals, which persist nowadays, allow the supply of water to lands far from the Nile which do not benefit from its annual floods.

Figure 5.2.8. *Egyptian representation of a plough*

5.2.4.3. Mathematics and Topography

Ancient Egyptians used the decimal system (additions, subtractions, multiplications, divisions). They even got to solve what today is understood as quadratic equations and square roots. They also possessed a wide knowledge in geometry. They calculated the surface of trapezes, squares, volumes, they knew the Pi number with a remarkable approximation (3.1605) and they established

[6] Hieroglyphic characters were used in Egypt in the monuments.

[7] Demotic writing was a simple and popular writing used in Egypt from around 660 BC.

[8] A *shadoof* or *shaduf* was an early tool used in irrigation by ancient Egyptians along the Nile River and Mesopotamia. Used as a lever it allows pumping water out of a well, a canal or a river.

length units such as the *royal cubits*[9] which were divided into *palms* and *hands*. Each pal was divided into 7 *fingers*. They applied these disciplines to their great constructions. Among the most important mathematical papyrus found in Egypt were the Rhind Mathematical Papyrus (*c*.1550 BC)[10] and the Moscow Mathematical Papyrus (*c*.1850 BC).

They determined the position of different points and the distance between them, information they used to create the bases of the pyramids and to redefine the boundaries of fields and properties affected by the annual flooding of the river (whose margins disappeared each year inundated by the waters).

5.2.4.4. Engineering and Architecture

They made some of the most impressive works of all time such as the wall of the city of Memphis (former capital 19 km from Cairo) to divert the Nile to the irrigated lands (2700 BC) and of course they also accomplished the construction of the pyramids of Djoser (Saqqara), the three pyramids of Giza, one of which can be seen in Figure 5.2.9 (among others) and the construction of innumerable and grandiose temples (about 2600 BC). Ancient Egyptians fabricated sailboats[11] to accomplish commercial transactions with other nations. The word *Sepy* means tying and was later used to designate the construction of wooden boats. The wood of the larger vessels was imported, since Egypt did not have much of this material. One of the most notable features of their boats was the absence of keel.

Figure 5.2.10. *The Sphinx and one of the Giza*

Imhotep (2700-2650 BC), who was a wise doctor and astronomer, marked the inflection point in Egyptian science. He was one of the first known engineer and architect in history. He is the author of the funerary complex of Saqqara, the step pyramid of Djoser. In addition to the construction of a six-step pyramid (Figure 5.2.10) with a height of 60 meters

Figure 5.2.9. *Saqqara's Pyramid of Pharaoh Djoser. It was built by Imhotep*

[9] Royal cubits were equivalent to 0,524 m and were used for roads and fields.

[10] The Rhind Mathematical Papyrus was probably a mathematics textbook, used by scribes to learn to solve mathematical problems. Eighty-four problems are included in the text.

[11] They were the inventors of this means of transport. The first boat to sail on the Nile was a simple boat made with papyrus stalks tightly tied together. Its uses were limited but its replacement was easy and cheap.

and excavated in the inside, it possesses an ensemble of galleries where the tomb of the pharaoh Djoser remains. It is surrounded by a wall of approximately 1500 meters of perimeter with several edifications. Imhotep also had to organize the process of a colossal construction, controlling the work of thousands of laborers. The pyramid of Djoser also has a mystic meaning. Before this pharaoh, the nobles and the kings were buried in *mastabas*[12]. Imhotep suggested to the pharaoh to build the tomb of the tombs for the King of the kings. For that, he conceived the idea of the superposition of *mastabas*.

5.2.4.5. Astronomy

It was one of disciplines they cultivated the most. The systematic observation of the sky, they were able to predict lunar and solar eclipses, floods of the Nile and the apparent movement of the planets, among other aspects.

Thanks to their studies, they prepared the oldest solar calendar of which there is evidence (Figure 5.2.11). In this calendar, one year was divided into 360 days that were grouped in 12 different months. Each day had 24 hours and was structured in two parts of twelve hours each. At the end of every year they had five epagomenal days that were exclusively dedicated to festivities. The Roman emperor Julius Caesar adopted this calendar. Later, Pope Gregory XII reformed it to establish the actual Gregorian calendar.

Figure 5.2.11. *Ancient Egyptian calendar*

5.2.4.6. Medicine

They had knowledge of cerebral anatomy and considered that the heart was the center of the human being. Because of their mummification practices, they were familiar with the anatomy of the human body. They performed surgeries and they even performed amputations. To replace the removed limbs, they made wooden prosthesis and slings to weld the broken bones. They also developed dental bridges. Also, they knew anesthesia, based on plants such as water lily, cannabis and opium poppy. They also developed a wide range of cosmetics as they were in the habit of applying makeup and taking care of their physical appearance. They used to paint the outline of their eyes and the material used to do so was an antibacterial that protected them from ocular infections. They also used oils to prevent sunburns.

[12] A *mastaba* is a type of Egyptian tomb in the form of a flat-roofed, rectangular structure with inward sloping sides.

5.2.4.7. Mummification

Due to their knowledge of the human body and the internal organs of both humans and animals, along with their embalmment techniques, they were able to preserve the bodies and keep them intact through the years by means of mummification.


Figure 5.2.12. *Imhotep's statue*

Imhotep (Figure 5.2.12), to whom has been referred before, was also the turning point in ancient Egyptian's medicine. He promoted the transition from a magical-religious medicine to an empiric-rational medicine based on experience and observation. He recommended the use of opiates as anesthesia that are associated with the first descriptions of cranial sutures and, above everything, he praised hygienic practices. He is considered the founder of Egyptian medicine as he gave a more empirical and rational perspective without using excessive magical treatments.

5.3. Chariots in history

A chariot is an open, two or four wheeled, vehicle of antiquity. It is believed that it was first used in funeral processions and it was later employed in warfare, racing and hunting. The first chariots that appeared in Asia and Europe were heavy ox-drawn conveyances with solid disk wheels (Chondros, Milidonis, Rossi, & Zrnic, 2016). One of the first chariots of which there is knowledge is dated of the 3rd millennium and appeared in the Standard of Ur[13]. The artist depicts the chariot in different states of motion. The portrait shows a four-wheeled chariot with solid wheels pulled by donkeys. The chariot is carrying a charioteer and a spearman. Later, chariots and wheels were improved by other nations such as the Hittites, the Achaeans or the Egyptians.

5.3.1. The Wheel

Despite the knowledge of the ancient Egyptians, the wheel, as well as the subsequent war chariot, was not a technological advance originating in Egypt. The Egyptian empire coexisted with other great empires. Given its geostrategic position, it had numerous cultural exchanges with other peoples. Ancient Egyptians acquired knowledge through contact with other peoples and through culture.

The wheel is, probably, one of the oldest mechanical inventions in the world and one of the most important. The exact moment of its invention is unknown even today. However, it is believed that the

[13] The Standard of Ur was found in the Royal Cemetery of Ur, in modern Iraq, by Sir Leonard Woolley in 1928.

first to use the wheel were the potters to create their vessels. Even though there is no historical evidence, it is believed that the first wheels appeared towards the 8000 BC in Sumer. Even so, one of the first wheels of which there is evidence dates to the 3500 BC. It was found in an archaeological excavation in Mesopotamia and it is thought to be the wheel of a potter.

The birth of the wheel made possible that animals could multiply the amount of material they carried while pulling a cart instead of carrying a limited amount of weight in their backs or in saddlebags. Among the experts' opinions is the possibility that the wheel was not used in transport until 300 years after its invention. A wheel that is believed to have been used in transport, either of people or objects, appeared in 3200 BC in Mesopotamia. These wheels were solid wheels, extremely heavy. They were formed by three wooden planks that were joined together with leathers or metals and joined to the axle by wedges that rotated with it.

Apparently, wheels dedicated to the transport could have been a slow evolution of the combination of the roller and the sled. It is known that the first men used rollers under heavy objects to move them more easily. In the same way, there is also proof that men used to situate skates under the heavy loads to lift them, which gave birth to the sled. However, the transport of heavy objects with rollers posed several problems and inconveniences. The use of two or more rollers meant they needed to be moved regularly to the front of the object for the later to slide over them.

Wheels were improved by other Asian cultures until, around 2000 BC, the spoked wheels were invented. It is unknown how the change from solid wheels to spoked wheels occurred. Neither is known the evolution wheels suffered until spokes were created, but if when relying in the Darwinian Theory of Evolution, it would be natural for the wheels to have evolved in that direction. According to the most important corollary of Darwinism, the evolution occurs by small increments rather than by great steps. The adaptive superiority of the spoked wheels over solid wheels in utilitarian vehicles is obvious. Spoked wheels are lighter, which facilitated the pull of the animals, and suspension is better as it is more flexible. Moreover, because the wheel is lighter, there is a less rapid deterioration of the rim of the wheel. If any part, or relation between parts, is not correctly executed, the spoked wheel is not superior but inferior to a good solid wheel. (Cloak, 1968)

It is thought that the solution was found in East Persia between the 2000 and the 1500 BC when they gradually eliminated parts of the disk, managing to reduce its weight until reaching what today is known as spokes. (Figure 5.3.1).

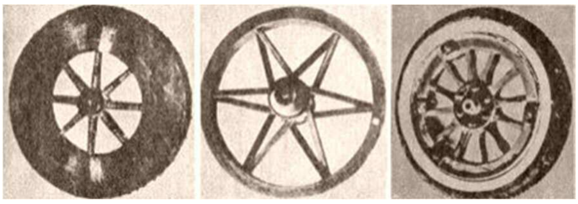

Figure 5.3.1. *Drawing of the gradual elimination of sections in the wheel*

Experts believe the wheel was introduced to Egypt by the Hyksos in the 16th century BC. One of the firsts wheels with spokes that has been recorded appeared in Egypt around 2000 BC in a chariot. Spoked wheels also appeared around that date in the Caucasus Region, Central Europe, China, Indus

Valley and North-western India. Strangely enough, there is no evidence of the use of wheels in the Americas until after contact with the European civilization. The Egyptian civilization improved them, obtaining the maximum sophistication when they built a light and efficient wheel around 1800 BC, approximately. They were one of the most characteristic items in the Egyptian war chariots, being one of the most polished and complex pieces of it.

Wooden wheels continued to be used for millennia. In 1000 BC the Celtics invented iron rims to put around the wheels, making them stronger. Wood, for its hardness and ductility, and depending on the technical possibilities of the time, was the ideal material for the construction of wheels that continued to be used until the development of the solid rubber tire. It is worth mentioning he slow evolution of this invention since, even though it was perfected, it did not undergo major modifications until the middle of the 19th century with the invention of the tire. In 1802 wire spokes with tension were invented and in the Industrial Revolution wheels were used in various machines and mechanisms. Since then, it is difficult to imagine a mechanized system without the presence of wheels or symmetrical components moving circularly around a shaft.

5.3.2. The Egyptian Chariot

The tomb of Tutankhamun, which was discovered on 1922 by Howard Carter and Lord Carnarvon, was found almost intact and is one of the best preserved of the Valley of the Kings. Its discovery was extraordinary as it is a unique tomb in the Ancient East. In addition to the many treasures that were found in it, the tomb offers us the possibility to compare between six almost full chariots of the New Kingdom and with other texts and representations from Egypt and other nearby cultures. These discoveries, as well as the Florence chariot[14] and numerous engravings and bas-reliefs, provide us with a very reliable portrait of how these chariots were and how they were used in Ancient Egypt.

The great pharaohs of the New Kingdom[15] (1550 to 1085 BC) made the war chariot the symbol and instrument of their power. There are many inscriptions that refer to chariots. Among them, one of the best known is the inscription that was found in Karnak, the words Thutmose III addressed to his army in the battle of Megiddo (15th century BC): "*Be firm, stay attentive*". It describes the Pharaoh mounted on his *Electrum*[16] war chariot accompanied by dozens of chariots that terrorized his enemies.

---

[14] The Florence chariot is an 18th Dynasty chariot found in a private tomb. Considered to be the oldest of the chariots, based on its four-spoked wheels and relatively narrow wheel track.

[15] Some of the great pharaohs of the New Kingdom were: Thutmose I, Thutmose III, Seti, Horemheb, Ramses II, and Ramses III.

[16] *Electrum* was a silver and gold alloy that caused the chariot to shine in the Sun, making it appear a divine instrument.

The symbology of the war chariot united with the power and divinity of the Pharaoh, making it an element that was considered sacred. It has already been discussed that in Ancient Egyptian culture the explanation of the world occurred through the myth. The Pharaoh represented the order. Therefore, it is observed in many bas-reliefs (such as the temple of Medinet) how the Pharaoh with his chariot spreads chaos among his enemies, protecting the order in Egypt. It is not a real image but an archetypical one, it represents a concept.

5.3.2.1. The battle of Kadesh and the Treaty of Kadesh

The battle of Kadesh (1274 BC) was the last battle from the Bronze Age that confronted two great empires: the Hittites of King Muwatali (Kingdom of Hattusa[17]) and the Egyptian of Ramses II due to their thirst of expansion. In Figure 5.3.3 a bas-relief that represents Ramses II in the battle of Kadesh on a war chariot and that was found in the temple of Abu Simbel can be seen. This battle ended in a draw and is important for several reasons. It is the first battle of which there is written record of both parties, therefore, both one version and the other are known. Besides, it is the first battle of which the subsequent peace treaty is preserved. In 1834 a French archaeologist named Charles Texier (1802-1871) found it in Hattusa, the ancient capital of Hatti. He found multitude of clay tablets with cuneiform texts. Among them, was the Eternal Treaty (as the signers referred to it). This treaty told a very different story from the one Ramses II had made the world believe, letting us discover, thirty centuries later, what had really happened. With this, it becomes clear that Ramses II performed the first campaign of propaganda manipulation by the power of which there is proof nowadays. The young Pharaoh, at the beginning of his reign, could not afford that defeat in front of his people. He ordered Pentaur, poet of the court, the writing of an epic poem that is now known as the *Poem of Pentaur* and he filled the temples with the transcriptions of this text, from Abu Simbel to Karnak, Luxor, etc. The poem represents Ramses who, in the moment when the Egyptian army was going to be defeated, emerges as the god he was considered and defeats the Hittites. He ensured the

Figure 5.3.3. *Bas-relief of Ramses II at the battle of Kadesh on a war chariot. Abu Simbel*

Figure 5.3.2. *Tablet of the Treaty of Kadesh*

[17] The Hittites were an Ancient Anatolian people who played an important role in establishing an empire centered on Hattusa, in North Central Anatolia around 1600 BC.

proclamation of both this poem and the war Bulletin (a limited version of the poem) throughout the country. Propaganda fulfilled its mission so well that specialists believed his version almost to this day.

The most important aspect of the Treaty of Kadesh (Figure 5.3.3) is that it is of an indefinite nature. To implement a long peace between the two countries, it ensures the limits of the common borders between the two empires and guarantees mutual assistance in case of confrontation with a third party. This pact achieved a great commercial activity between both parties from then on. For example, the Hittite iron arrived in Egypt, which allowed it to come out of the Bronze Age. It is worth noting two women, Puduhepa queen of Hatti and Nefertari queen of Egypt, who played a fundamental role a worked to make the treaty possible. It is documented that the two queens maintained a communication by correspondence of fraternal and diplomatic nature, both before and after the signing of the treaty. It should be remembered that, unlike other cultures, women in Egypt held important positions, both private and public[18]. Puduhepa was also represented as an equal next to her husband, king Hattusuli III. Even though not many have been preserved, there are references to the letters as precursors and mediators of this peace, a piece that lasted until the disintegration of the Hittite empire.

5.3.2.2. Technology of the Egyptian Chariot

The Egyptian war chariot is, without any doubt, one of the most curious and famous weapons of Ancient history. The simple idea of a horse-drawn chariot, which granted velocity and an effective attack against the enemy, was divulged by the Egyptians in their battles even though many ancient civilizations at some point in their history counted with it. Their conservative nature did not prevent the Egyptian culture from assimilating the chariot in less than a century from its appearance in 1600 BC. It became an extremely effective instrument of war that was dominated with absolute mastery in the times of Thutmose III[19] and which made possible the Egyptian influence and its expansion.

The chariot, a representative symbol of the monarchy in the New kingdom, is not an instrument that comes from the Egyptian culture, but an artifact inherited from their enemies. Most of the authors coincide in dating the appearance of the chariot between 2600 and 2000 BC in Sumer (Cabrero, 2018). The Sumerian cities-state built these chariots of two to four wheels, pulled by

Figure 5.3.4. *Ancient Sumerian chariot*

[18] Egypt was governed in many occasions by women. Hatshepsut was one example.

[19] Thutmose III was the sixth Pharaoh of the 18th Dynasty of Egypt (*c.*1479 BC to 1425 BC).

hemiones[20], that had solid wooden wheels and fixed axles, as seen in Figure 5.3.4. They began to be used in war pulled by asses and with a crew of two men armed with spears and axes. It is thought they could be used as a command post for the officers or to provide a transport service to the battlefield.

Regardless of their primary objective, over the decades these inventions evolved towards much more mobile transports. The Hittites, and later the Hyksos, perfected this chariot, which formed the professional nucleus of their armies. The battle of Kadesh is considered the largest battle of war chariots of antiquity, 3700 of these chariots fought on the Hittite side. However, it was a heavy cavalry of three men by yoke, which required a centered axle of the cabin and that subtracted maneuverability. The three men were armed with spears and shields and used bows and arrows in the cargos. These gave strength to the army since they were strictly offensive weapons that served to break the formation of the enemy infantry; it is believed that many had sharp protrusions on the wheels. Its problem was its slowness and poor manoeuvrability.

5.3.2.3. Tactical Utilization of the Egyptian Chariot in the Pharaoh's Army

Every empire has as foreign policy to impose its dominion over other nations. This dominion is supported by the army and for the development of great empires like the Egyptian it was needed a powerful, disciplines, well organized army, along with well-trained units with great capacity of mobility and a great offensive power. Meaning what can be referred to as the *Imperial Weapon*, on which the tactics and strategies of the army are based.

The war chariots were, as already explained, a fundamental part in the Egyptian army for many centuries allowing the development and the expansion of the empire as a great power. They had two basic tactical uses:

1. As mobile platforms for weapons (transporting an archer)
2. As a way to test the enemy infantry units by means of cargos that, given their flexibility and maneuverability, allowed them to shoot arrows from any position and in different directions creating chaos and confusion among their enemies.

With the introduction of the chariot, the army was divided into two parts: the infantry and the war chariots. The first were formed by companies of 200 men distributed in sections of 50 that formed the first line phalanx. Their armies, like the ones of their enemies, were the arch, the arrows and the shields they used as protection. These bronze arches gained quality with time. There were 25 chariots for each company and it is believed that there were two types of chariots: those with six spokes for combat and those with four spokes, lighter, for exploration. Also, chariots were surrounded by the infantry to protect them.

[20] *Hemiones* were Asiatic wild asses.

Tactically, each army corps, which could act independently, had 300 to 500 chariots but all of them, in case of necessity, fell under the authority of the commander (a new military figure and of the Pharaoh's court). An example was Yuya's chariot. Yuya was buried next to this light chariot. This chariot is square-shaped and is covered in red colored leather. The wheels appear to be almost intact, which makes experts believe this chariot was especially made for the burial of the couple. The low height of this chariot and the half-closed rear also seemed especially designed for an elderly person.

So, two or more corps of the army were combined to present battle. This flexibility in the chain of command, so typical of the Egyptian armies, explains to a large extent their triumph in Asia, before armies whose organization was more rigid tactically and less strategically coordinated.

5.3.2.4. Decline of the War Chariot

With the improvement of the tactics of infantry, the modification of the formation of the phalanx and the appearance of soldiers on horseback (Alexander the Great) the car was losing its power and utility. It is believed that the last to use chariots in battle in the Western world were the Celts against the Romans in the 4^{th} century BC.

It is important to note that the existence of the figure of the rider was possible due to the evolution suffered by the horse races. As they were bettered, bred in captivity, they got bigger and stronger (the first horses descended from wild animals and were only a little bigger than a pony). Thanks to this, the cavalry appeared. It was more effective since horses could be used in all types of terrain and, in addition, the economic cost of building a chariot was avoided.

6. Tutankhamun's Chariots

6.1. Introduction

In 1922, Howard Carter discovered the tomb of Tutankhamun in the Valley of the Kings in Egypt. Among the 5398 items that were found in the tomb, there were six dismantled chariots. Four of the vehicles (A1, A2, A3 and A4) were found in the Antechamber. The other two chariots (A5 and A6) were found in the Treasury. The original notes on the chariots and the other items found in the tomb are now in the Griffith Institute (Oxford) along with the rest of the Carter archive (Littauer & Crouwel, 1985). The following descriptions have been taken mainly from the Littauer and Crouwel book *Chariots and Related Equipment from the Tomb of Tut'ankhamun* and were verified thanks to the visit to the Grand Egyptian Museum.

6.2. The Visit to the Grand Egyptian Museum

During the summer months I had the opportunity to visit Cairo. The purpose of this trip was to visit the Egyptian Museum and see Tutankhamun's chariots personally to take pictures for the project.

The Grand Egyptian Museum is a planned museum of artefacts of ancient Egypt. It is as the largest archaeological museum in the world; it is still under construction and is scheduled to be partially open in 2018 exhibiting the full Tutankhamun collection with many pieces to be displayed for the first time. The museum is sited on 50 hectares of land approximately two kilometres from the Giza pyramids and is part of a new master plan for the plateau. Currently, only the Conservation Center, where some of Tutankhamun's artefacts have been moved to be restored, has been finalised and is open for the specialists to work on the artefacts.

Once the trip had been planned, I found some information that stated that some of the chariots had been moved to the new Egyptian museum to be restored. In fact, the last of Tutankhamun's chariots had been moved to the restoration center in May. Since the information was not reliable, I sent some emails to the museum asking for more information but got no response.

When we arrived at the Egyptian Museum, we managed to talk to the General Director of the Egyptian Museum, Sabah Abd El Razik Saddik. She was very kind and told us the Grand Egyptian Museum was not open to tourists. To enter the Conservation Center it is needed to fill in some forms for the Ministry and pay some taxes. However, she gave us her card and encouraged us to go to the Conservation Center and ask for doctor Tarek Tawfik, Director of the Grand Egyptian Museum, to try to see the chariots or talk to a specialist.

Figure 6.2.1. Visit at the Wood Conservation Center (Grand Egyptian Museum).

We went to the Conservation Center but it was a holiday and no experts were there. The security guard told us to go the next day and ask again. The next day, we went back to the Conservation Center and the PR of the Grand Egyptian Museum received us. I explained my situation to her and she contacted Doctor Tarek Tawfik. Although we could not speak directly to him, he exceptionally allowed us to enter the Conservation Center and see the chariots.

It was one of the best experiences in my life and a very enriching one. To be able to see all those treasures being restored from a close look, the restoration team and all the equipment was truly exceptional. Moreover, I was able to talk to one of the conservators, Mohamed Moustafa, who answered all my questions and provided me with new information about the chariots. He explained to me they were using non-destructive techniques to determine the composition of the chariots such as Spectral Imaging. Therefore, the results about the material composition were not conclusive. Nevertheless, they thought the wood used was very likely to be elm wood.

He offered to solve any other doubts that could arise and sent me some important datum about the chariots. Thanks to him I could correct some information I had wrong, such as the weight of the chariots and some of their measurements.

They even encouraged me to send the project to them and invited me to the annual conference about Tutankhamun if the project proved new information about the chariot.

6.3. Description of the Chariots

All the chariots were custom-made and there are not two chariots that are the same. It is thought they used woods such as elm, birch and tamarisk from Syria and Lebanon since Egypt was not a producer of wood. The ash tree was used for the axle. There is evidence that in some cases the trees were cultivated in special orchards and their trunks were manipulated to grow with a certain shape. This is the case of the poles of some chariots. These chariots were not made for rocky terrains as they could break or flip. Nonetheless, they were the ideal weapon for Egyptian terrains; they were extremely efficient in open and flat grounds.

The six chariots found in the tomb of Tutankhamun are all similar in construction and proportions. In this chapter the different parts of the chariot will be described to provide the reader with a better understanding of how they were built.

The following image (Figure 6.3.1) is a drawing from *Chariots and Related Equipment from the Tomb of Tut'ankhamun* (Littauer & Crouwel, 1985). This figure will help the reader become familiar with the different parts of the chariot and recognize them.

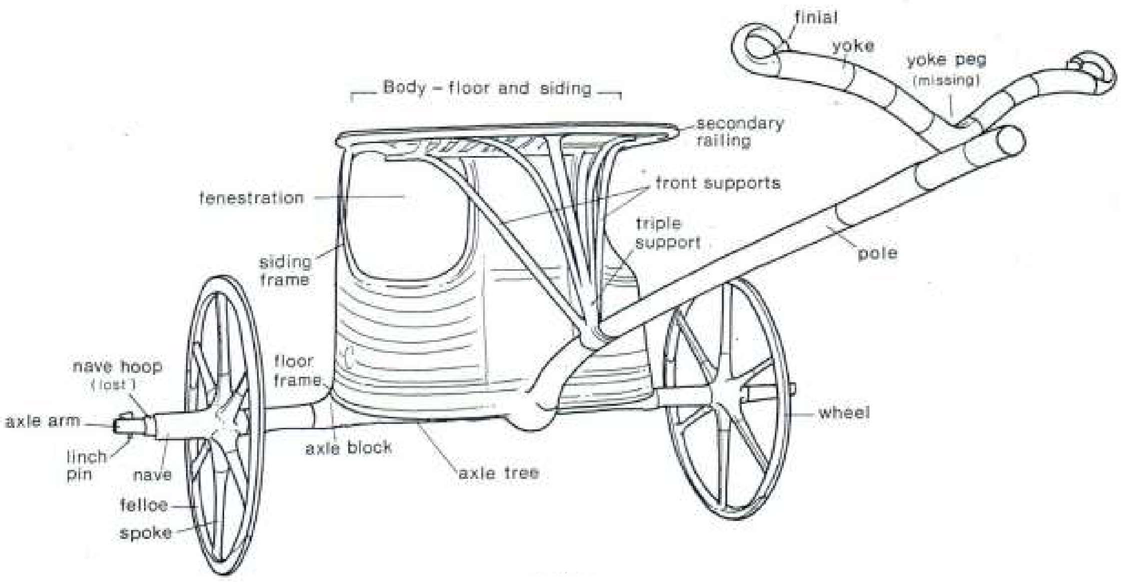

Figure 6.3.1. *Drawing of the Tutankhamun class chariot.*

6.3.1. Body

The construction of the body of the chariots consists of a D-shaped floor frame and a siding frame that were bound together and tied to the axle.

6.3.1.1. Floor Frame

The floor frame consists of two pieces of straight-grained wood, artificially bent and overlapping at the center front. The two parts were glued and bound together with thongs.

The rear floor bar is flat and has a rectangular shape. It joins the ends of the curved parts to form the D shape. Underneath this floor bar there is a U-shaped block of wood that acts as a socket for the pole. It has a rectangular hole where the end of the pole fits.

6.3.1.2. Siding Frame

The siding frame follows the same horizontal curve as the floor frame. It is made of two artificially bent woods bound together at the center part of the siding frame.

6.3.2. Axle and *Linch* pins

The axle of the chariots is made up of a single piece of straight grained wood. The axle has a pear-shaped section in the middle part and a circular section in the ends of the axle (arms). The length of the axles varies from 2,13 to 2,36 meters. This length allowed a wide wheel track and prevented overturns (lateral stability). It also allowed long wooden naves that were essential if the wheels were not to wobble badly. The axles were attached to the bodies in the ends of the siding frames by vertical tenons. They were mortised to the floor frame cradles at the rear part of the body.

Traces of red leather were found in the inner part of the naves of the wheels. The leather that covered the nave up to the spokes had a loose cover that allowed the wheels to turn freely. Lubricant, probably animal fat, was found between the axle and the naves. The grease prevented friction and wear of the axle. Since dust and sand were found between the naves and the axle, it is believed that the function of the leather sleeve was to prevent the lubricant from splattering the chariot or its occupants. Some chariots had parts of the axle covered in metal sleeves that reduced friction between the axle and the naves.

The *linch* pins had a simple rectangular shape with a decorated head. They were placed in the outer ends of the axles in rectangular holes. They held the wheels in place.

6.3.3. Wheels

The wheels are one of the most characteristic, complex and refined parts of the chariots. The wheels that were found in the tomb are all six-spoked wheels and the diameter varied from 0.89 to 0.97 meters. The wheels are formed by six V-shape spokes with a semi-elliptical section that were glued together and pressed into the nave of the wheel.

The nave and the spokes were bound together with raw-hide strings and glue. When these strings dried, they contracted, forming a light and very strong bound. The felloe of the wheels is formed by two pieces of artificially bent wood of different lengths that were bound and glued together (mitred). The nave of the wheel was carved from a single piece of wood until it got the desired form for the spokes to adjust properly.

The wheels had long naves to prevent wobbling on the wooden axle by extending the nave in both directions by adding cylindrical flanges. The interior of the naves was protected by leather linen, which reduced the noise. A lubricant was found in the linings. The lubricant decreased considerably the friction between the interior of the naves and the axles and it was believed to be animal fat. An analysis performed by Dr. Nasry Iskander on the grease residue taken from molecules on the bearing surfaces confirmed it was animal fat. The fat impeded contact between the wood from the axle and the wood from the nave, which ensured low friction between the two parts. Without the grease, the friction coefficient f between the two parts of wood would have been of 0.25. When grease is used, this coefficient f is reduced to 0.1 (Rovetta, Nasry, & Helimi, 2000).

The spokes gradually narrow towards the felloes into which they are mortised. However, this narrowing of the felloes could be an effect created by the binding beneath the layer of gold and gesso at junction of the spoke and the nave. The spokes were secured to the felloe by means of a rectangular block and wedges that tightened the connection.

The felloes were composite. There two felloes of unequal lengths of artificially bent wood overlapping and secured with raw-hide binding. In addition, a wooden tire composed by four sections of wood was placed on top of the felloe. They were bound by bark-covered leather and by bronze thongs.

6.3.4. Pole

The poles are made of a single piece of straight-grained, artificially bent wood. They varied in length from 2,43 to 2,60 meters. They were perfectly tied with leather strips to the front floor bar and were let loose at rear bar of the floor frame where it laid inside a U-shaped socket. This socket allowed the pole to move back and forth freely and acted as a shock absorber.

The pole has a semi-elliptical shape in the rear and the front part where it was usually flattened to form a seat for the yoke. The middle part of the pole has a drop shape section and is shaped in a curve with an oblique angle.

6.3.5. Yoke

The lengths from the six yokes found in the tomb vary from 0,825 to 0,96 meters. The bearing parts were covered in leather. These parts include the area of the center depression as well as the areas on both arms at the top of the arch.

The yokes rested on top of the poles secured by yoke pegs and lashings. A wooden washer, concave on top and flat below was placed between the yoke and the pole. As already mentioned, the latter was usually flattened in this area to allow the yoke to sit on top of it.

6.3.6. Other Parts of the Chariots

There were many other parts that formed the chariots and many different pieces and decorations were found in the tomb. However, because they were not essential for this study.

These parts are thoroughly described in *Chariots and Related Equipment from the Tomb of Tut'ankhamun* from M.A Littauer and J.H Crouwel. They were yoke saddles, hawks and disks from the poles, check rowels, blinkers, bridle bosses, appliqués from the Harnesses, neckstraps and housings, whips, double-pointed sticks, dagger-shaped objects and fly whisks (Littauer & Crouwel, 1985).

6.4. Materials of the Chariots

The chariots were mainly constructed of different kinds of woods. Unfortunately, very few analyses have been made on the chariots to determine which type of woods constitutes them. Elm was identified by L. Chalk and L. A. Boodle in naves, spokes, felloes, axle and pole in the different chariots. Boodle also identified birch bark (*Betula verrucosa*) covering parts of the chariots. Since elm and birch are not native to Egypt, they may have been imported from North Africa, Western Asia or Europe.

The properties of elm make it susceptible to heat-bending, which would have made it a perfect choice for the construction of the chariots that required a lot of bent wood. Birch bark on the other hand, has waterproofing properties that helped protect the joints and important parts of chariots from humidity, preventing the joints from loosening. Overlays of gesso and gilding were often used as well to protect the wood from external agents.

It is unknown whether the straight-grained wood was bent exclusively by means of hot-bending or if certain parts were trained to a shape while growing. However, it seems likely that both methods were used to acquire the desired shapes.

7. Mechanical Analysis of the War Chariot

7.1. Mechanical Properties of Wood

The materials used for the construction of the chariots, as commented above, were woods coming from other countries such as the Lebanon. It is believed that different types of woods took part in the construction of the chariots. However, no thorough analyses have been made to determine these types of woods. Some analyses claimed that one of the main woods used was elm. Therefore, in this study the chariot will be considered to be made completely of elm (*Ulmus procera*).

7.1.1. Elastic properties

Wood is an anisotropic material which means its properties show considerable differences if the loading is axial (parallel to grain) or transverse (Figure 7.1.1). The study of an anisotropic material is, therefore, more complex than the study of an isotropic material. Twelve constants (nine are independent) are needed to describe the elastic behavior of wood: three moduli of elasticity E, three moduli of rigidity G, and six Poisson's ratios μ (Kretschmann, 2010). The moduli of elasticity and Poisson's ratios are related by the following expressions:

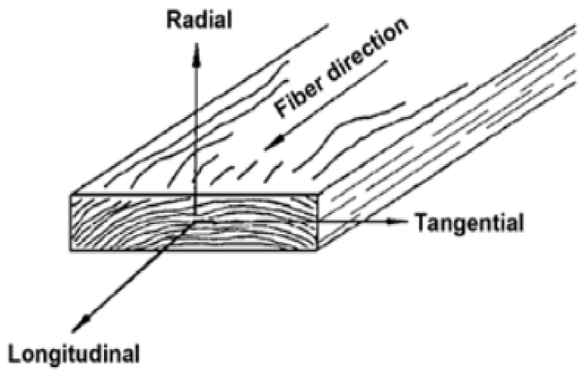

Figure 7.1.1. *Three principal axes of wood*

$$\frac{\nu_{ij}}{E_i} = \frac{\nu_{ji}}{E_j}, \quad i \neq j \quad i,j = L,R,T$$

Equation 7.1.1. *Moduli of elasticity and Poisson's ratios relation*

7.1.1.1. Modulus of Elasticity

Elasticity implies that the deformations produced by low stresses are completely recoverable after the loads are removed. When loaded to higher stress levels, plastic deformation or failure occurs.

When it comes to woods, three moduli of elasticity must be considered. E_L, E_R and E_T are the longitudinal, radial and transverse moduli of elasticity respectively. Data for E_R and E_T is not extensive. As stated in the *Wood Handbook* (Kretschmann, 2010), "*The modulus of elasticity determined from bending, E_L, rather than from an axial test, may be the only modulus of elasticity available for a species*".

7.1.1.2. Poisson's Ratio

It is the ratio of the transverse to axial strain. There are six Poisson's ratios for wood depending on the direction of the load and the perpendicular deformation that wants to be studied.

No Poisson's ratio could be found regarding the elm species, which is considered a hardwood. Table 7.1.1 (*Wood Handbook* (Kretschmann, 2010)) shows Poisson's ratios of different species of hardwoods. The two first columns show the Poisson's ratios for a longitudinal load applied to a wood member and a radial and transverse deformation. The average of these two columns is 0,41 ≈ 0,40, which is the value that will be used for the Poisson's ratio in this study.

Species	μ_{LR}	μ_{LT}	μ_{RT}	μ_{TR}	μ_{RL}	μ_{TL}
Hardwoods						
Ash, white	0.371	0.440	0.684	0.360	0.059	0.051
Aspen, quaking	0.489	0.374	—	0.496	0.054	0.022
Balsa	0.229	0.488	0.665	0.231	0.018	0.009
Basswood	0.364	0.406	0.912	0.346	0.034	0.022
Birch, yellow	0.426	0.451	0.697	0.426	0.043	0.024
Cherry, black	0.392	0.428	0.695	0.282	0.086	0.048
Cottonwood, eastern	0.344	0.420	0.875	0.292	0.043	0.018
Mahogany, African	0.297	0.641	0.604	0.264	0.033	0.032
Mahogany, Honduras	0.314	0.533	0.600	0.326	0.033	0.034
Maple, sugar	0.424	0.476	0.774	0.349	0.065	0.037
Maple, red	0.434	0.509	0.762	0.354	0.063	0.044
Oak, red	0.350	0.448	0.560	0.292	0.064	0.033
Oak, white	0.369	0.428	0.618	0.300	0.074	0.036
Sweetgum	0.325	0.403	0.682	0.309	0.044	0.023
Walnut, black	0.495	0.632	0.718	0.367	0.052	0.036
Yellow-poplar	0.318	0.392	0.703	0.329	0.030	0.019

Table 7.1.1. *Poisson's Ratios for various species of hardwoods from the Wood Handbook.*

7.1.1.3. Modulus of Rigidity

Also called shear modulus, indicates the resistance to deflection caused by shear stresses. Wood has three moduli of rigidity G_{LR}, G_{LT} and G_{RT}, where LR, LT and RT are the planes of the elastic constants respectively.

7.1.2. Strength Properties

The most common ones are:

- **Modulus of Rupture:** maximum load-carrying capacity of a member in bending. It is an accepted criterion of strength, although it is not a real value since the formula by which it is computed is only valid to the elastic limit.
- **Compressive strength parallel to grain:** maximum stress sustained by a compression parallel to grain.
- **Tensile strength parallel to grain:** maximum tensile stress sustained in direction parallel to grain.

7.2. Mechanical Properties of Wood used to perform the Analyses (*Ulmus Procera*)

When searching for the anisotropic properties of elm wood, there was data missing that could not be found. After realizing a comparative study of the axle of the chariot with the anisotropic properties of the wood and the properties parallel to the grain, no significant differences were found (Appendix B).

For that reason, only the mechanical properties parallel to the grain, which have a better mechanical behavior, will be considered. This simplification is possible because the wood was bent, instead of cut, to form the shape of the chariots. Therefore, the grains had the same direction as the shape of the different parts of the chariot which guaranteed the wood grains worked in the optimal direction (parallel to the grain) to achieve the wood's maximum performance.

In Table 7.2.1 some of the mechanical and physical properties of elm (Tsoumis, 1991) that will be used to perform the analysis are shown:

PROPERTIES	
Density	670 kg/m^3
Tensile Yield Strength parallel to the grain	78 MPa
Compressive Yield Strength parallel to the grain	55MPa
Young's Modulus or MOE	10780 MPa
Modulus of Rupture or MOR (bending)	87 MPa
Poisson's Ratio	0,4

Table 7.2.1. *Mechanical and physical properties of the elm species Ulmus Procera*

7.3. Structural Analysis Equations

For the structural analyses, elm will be considered a fragile material. Fragility is a measure of a material's inability to undergo significant plastic deformation before rupture. Although wood can undergo significant deformation before it breaks, it can be considered a fragile material.

7.3.1. Deformation Equations

The deformation of the parts due to axial loads or bending will be calculated through Castigliano's method. The second method of Castigliano enunciates that "*If the strain energy of a linearly elastic structure can be expressed as a function of generalized force Q_i then the partial derivative of the strain energy with respect to generalized force gives the generalized displacement qi in the direction of Q_i*".

$$\delta = \int_0^l \left(\frac{N_x}{EA} \frac{\delta N_x}{\delta P} + \frac{T_y}{GA_1} \frac{\delta T_y}{\delta P} + \frac{M_x}{EI_x} \frac{\delta M_x}{\delta P} + \frac{M_y}{EI_y} \frac{\delta M_y}{\delta P} + \frac{M_z}{EI_z} \frac{\delta M_z}{\delta P} \right) dx$$

Equation 7.3.1. *Castigliano's deformation equation*

Where:

- Shear Modulus: $G = \frac{E}{2 \cdot (1+\nu)}$
- I: Moment of inertia
- A: Section
- P: Load
- A_1: Reduced area

7.3.2. Maximum Stress Criterion

The maximum stress criterion assumes that a material fails when the maximum principal stress σ_1 in a material element exceeds the uniaxial tensile strength of the material. Alternatively, the material will fail if the minimum principal stress σ_3 is less than the uniaxial compressive strength of the material. If the uniaxial tensile strength of the material is σ_t and the uniaxial compressive strength is σ_c, then the safe region for the material is assumed to be

$$\sigma_c < \sigma_3 < \sigma_1 < \sigma_t$$

Equation 7.3.2. *Maximum stress criterion*

8. Finite Element Method

The finite element method (FEM), is a numerical method for solving problems of engineering and mathematical physics. The analytical solution of these problems generally requires the solution to boundary value problems (differential equations together with a set of additional constraints or boundary conditions) for partial differential equations. The FEM subdivides the problem into smaller size problems which are called finite elements. The subdivision of a whole domain into simpler parts has several advantages, such as:

- Accurate representation of a complex geometry
- Inclusion of dissimilar material properties
- Easy representation of the total solution
- Capture of local effects.

Basically, FEM is an iterative method that allows us to study a complex model by dividing it into smaller parts with their own differential equations and boundary conditions. When the smaller problems have been solved they are put together in a larger equation system and the solution is approximated by reducing the error in every iteration.

The finite element analysis is used in engineering to simulate, improve or solve complex geometries. The analysis usually has three phases:

1. Pre-process: it consists in the definition of the geometry, the generation of the mesh, the boundary conditions and the assignation of the material properties. Sometimes a preconditioning is made to ensure a better approximation or a better convergence of the calculation.
2. Calculation: the result of pre-process, in a non-time-dependent problem, allows to generate a set of N equations and N unknown quantities that can be solved with any algorithm for the resolution of linear equation systems. When it is a time-dependent problem, the resolution of the problem is iterative.
3. Post-process: magnitudes derived from the values obtained for the nodes are calculated, and smoothing, interpolation and even determination of approximation errors are sometimes applied.

For the resolution of the analyses of this project Ansys, which is engineering simulation software, will be used.

ANSYS

8.1. Chariot Model for the Finite Element Method Analyses

As explained in section 6, although the chariots were of similar construction and proportions, they were not identical. Therefore, the initial idea was to choose the measurements of one of the six chariots found in the tomb of Tutankhamun to create a model that could be used to perform the finite element analysis.

Chariots and Related Equipment from the Tomb of Tut'ankhamun (Littauer & Crouwel, 1985) contains drawings with scales that Howard Carter made when the tomb was found. The drawings do not have detailed measurements for each one of the parts and the scales from different drawings differ significantly.

To solve this problem, it was decided to take some of the most representative measurements of the chariot, such as the axle length or the wheel diameter, and adjust the other parts of the chariot to them, using pictures and drawings as a reference.

The creation of the model for the study was a long process where the assembly of the different parts had to be the most realistic one. The model of the study underwent some modifications to make the analyses easier and faster. The following sections present some of the most important parts of the designed chariot model for this study and the changes applied to the initial model (Figure 8.1.1) and the simplifications made to every one of the parts.

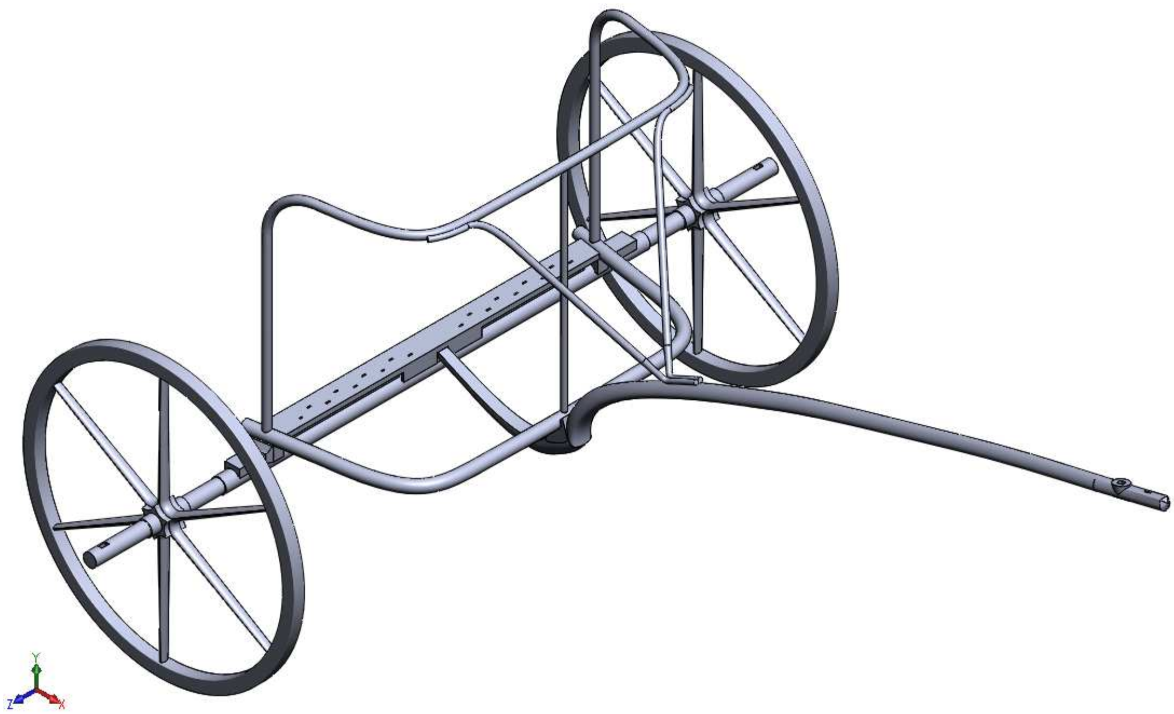

Figure 8.1.1. *Isometric view of the model used in this study.*

8.1.1. Wheels

As commented above, wheels were one of the most important and complicated parts of the chariot. They were light, resistant and resilient. Spoked wheels are more flexible and lighter than solid wheels, which made the Egyptian chariot much lighter. However, spoked wheels are not as resistant as solid wheels. The construction of Egyptian chariot wheels with V-shaped spokes made them more resistant than regular spoked wheels.

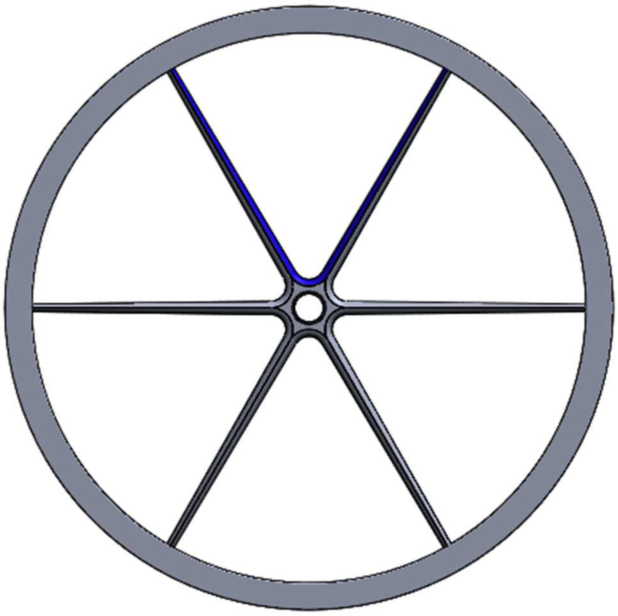

Figure 8.1.2. *Side part of a wheel. The ends of the spokes are embedded in the felloe to simplify the analyses. The shape of the spokes is shown in blue.*

Some simplifications have been made to perform these analyses. The parts of the wheel attached with raw-hide bindings have been considered embedded, which adds more rigidity to the wheel complex. Even so, it is a sufficiently accurate premise since the raw-hide bindings tightened when they dried, creating a rigid and light bound between parts. The spokes were mortised into the felloes. However, the spokes will be considered embedded as well. The felloes will be constructed as a single piece of wood, with no junctions between parts (Figure 8.1.2). This is due to the lack of information about the type of union between the two parts of wood that shaped the felloe and their dimensions.

As explained in section 6.3.3, wheels had long naves (Figure 8.1.3) to prevent them from wobbling[21]. However, it has not been necessary to include long naves to perform the finite element

[21] *Chariots and Related Equipment from the Tomb of Tut'ankhamun* (Littauer & Crouwel, 1985)

analyses since the axle and the wheel hole have the same measures and, due to the kind of contact between them, the wheel does not wobble. Figure 8.1.4 and Figure 8.1.2 show the nave of the wheel, where the spokes were adjusted and mortised, and the shape of a spoke respectively.

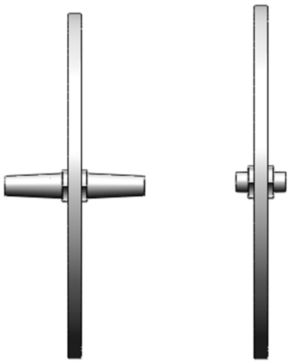

Figure 8.1.3. *Front part of the wheel. The long naves of the wheel are visible from this angle in the first picture. The second picture shows the wheel used for the study.*

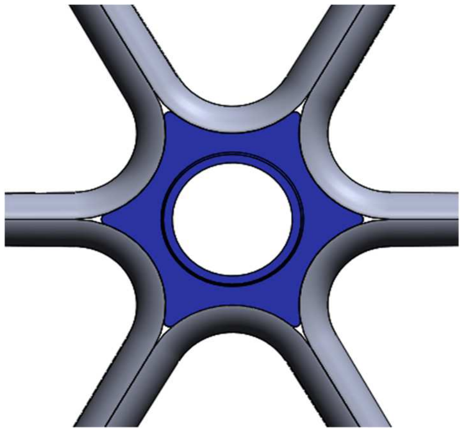

Figure 8.1.4. *The nave (in blue) of the wheel was carved of a single piece of wood.*

8.1.2. Pole

The pole has remained as close to reality as possible (Figure 8.1.5). It is an important part of the chariot structurally and its shape is a part of the cushioning system. The rear part of the pole has a square-shaped end that is set inside a U-shaped socked in the rear part of floor of the chariot that prevents the axle from rolling over.

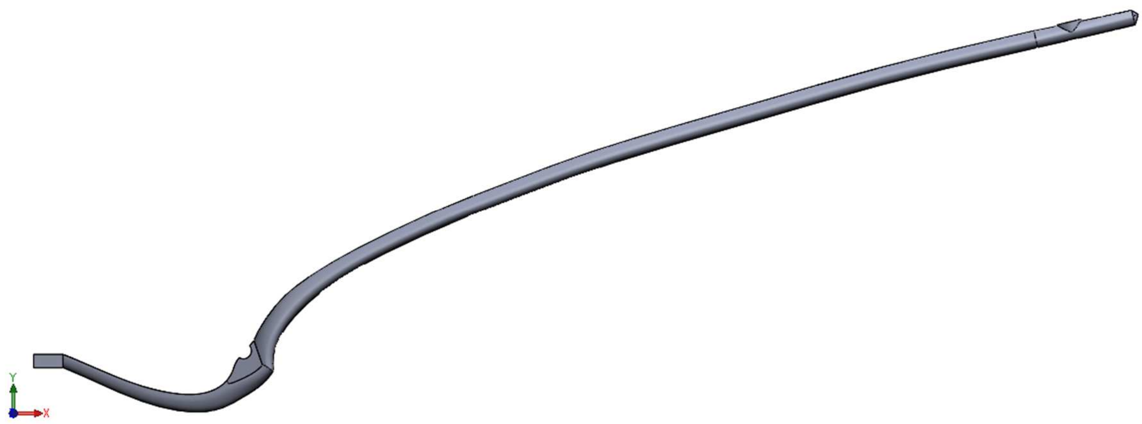

Figure 8.1.5. *Side view of the pole.*

The function of the rear part and the U-shaped socket was to act as a bow. The pole was perfectly attached to the front part of the floor of the body and was let loose inside the socket. This allowed the pole to move back and forth freely, acting as a bow and cushioning the ride. At the same time, as commented above, it prevented the axle from roll-overs.

8.1.3. Axle

The axle used in this study is a single piece of wood axle with a round shape. The axle narrows in its ends to accommodate the wheels, leaving enough place for the long naves to be accommodated (Figure 8.1.6).

Figure 8.1.6. *Front view of the axle.*

8.1.4. Body

As stated above, the body consists in different parts of wood attached together by means of leather strips or raw-hide bindings. For this study, attachments will be considered as an embedment. Therefore, the junctions between parts will be considered perfectly tied, with no possibility of loosening.

The floor made of linings will not be considered in the study as its function was to support the charioteers and it did not have any structural function. The forces representing the loads applied to the floor will be moved to the axle by means of other forces and moments.

The bars that went from the siding of the body to the pole (Figure 8.1.7) strengthened the body structure and prevented the siding bar from breaking or flex excessively. The vertical bar helped stiffen the structure.

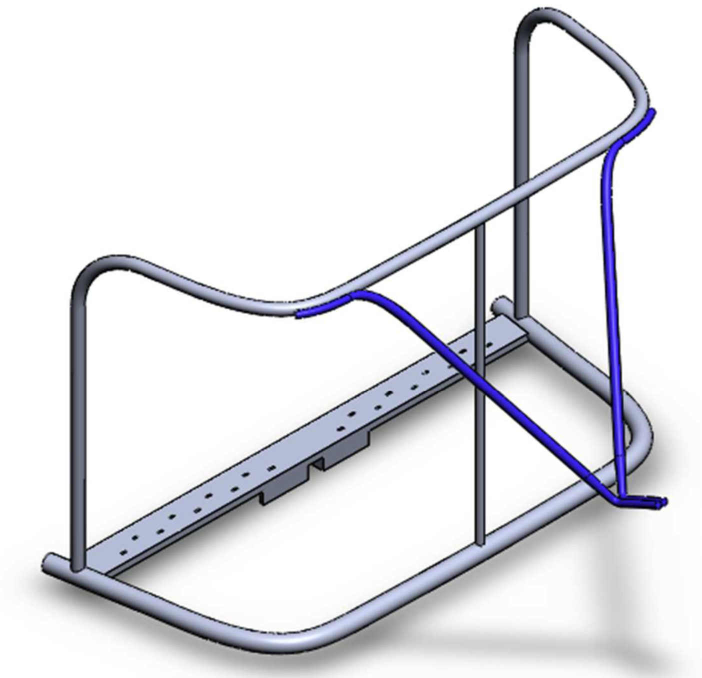

Figure 8.1.7. Isometric view of the body of the chariot. The bars coloured in blue went from the siding of the body to the pole.

The rear part of the floor has a U-shaped socket (Figure 8.1.8) where the rear part of the pole fitted and where the pole was let loose. As explained above, this mechanism acted as a cushioning, making the ride more comfortable, especially when the horses started to pull or in stops.

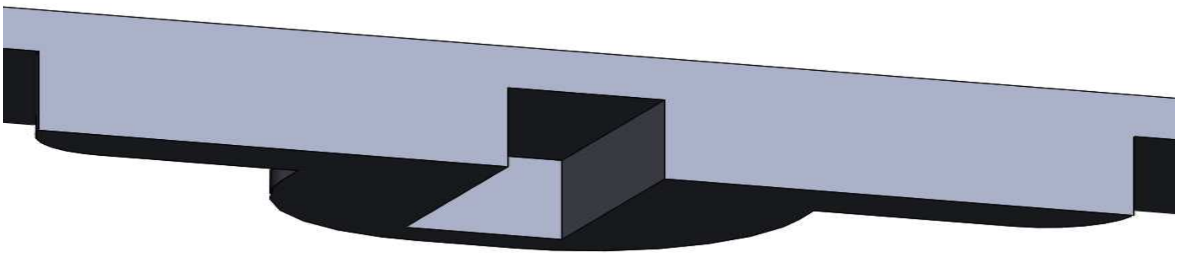

Figure 8.1.8. U-shaped socket.

8.2. Relevant Measures

DISTANCES	
Wheel track (L)	1,76 ≈ 1,8 m
Outer wheel diameter (D)	0,89 ≈ 0,9 m
Floor depth (th)	0,46 m
Body sidings height (h)	0,72 m
Pole length (L_p)	2,45 m
Wheel width (e)	0,035 m

Table 8.2.1. *Distances between parts of the chariot used in the study*

8.3. Mesh

The objective of meshing is to subdivide the model into a finite number of regions. The mesh is the degree of approximation our model has to reality. The denser the mesh, the smaller the error will be. However, a denser mesh will consume more the resources of the software and it takes more time to calculate. The dependence of the solution to the mesh is obvious. However, a very dense mesh is not always the best option. To determine the suitability of a mesh different tests with meshes of different sizes and complexities must be performed and the results between them need to be compared.

Because of the complex shape of the different parts of the chariot, the mesh used in this study is a quadratic mesh. The quadratic mesh provides a more accurate answer to the deformations, especially in 3D models with curves. The chosen mesh is a proximity mesh with a minimum proximity mesh size of 0,01 m (Figure 8.3.1).

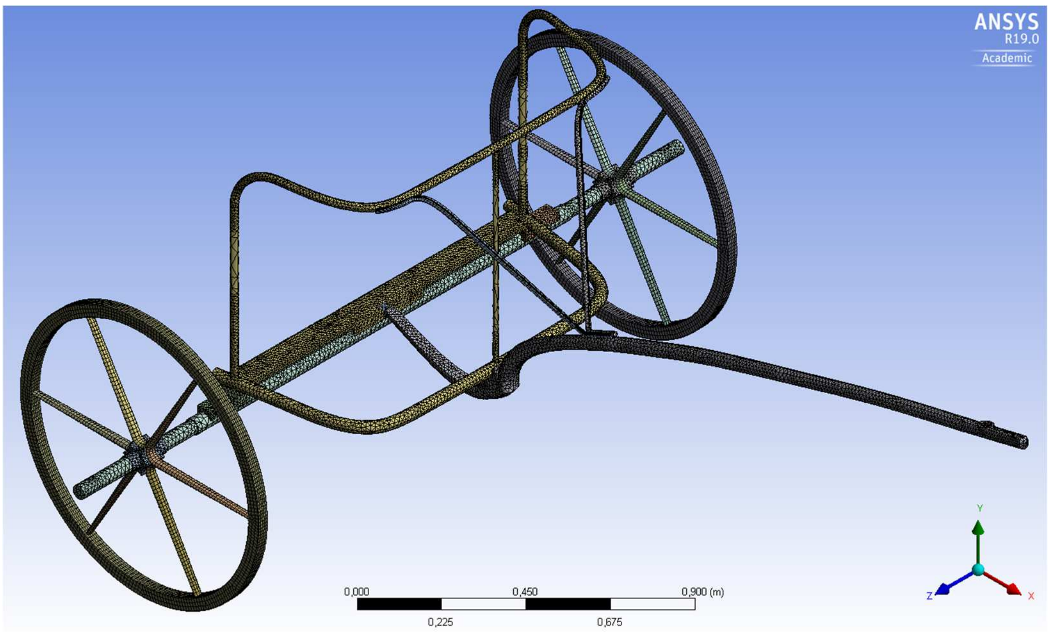

Figure 8.3.1. *Mesh*

9. Simulation of the Tutankhamun Class Chariot

9.1. Loads Applied to the Chariot

To determine the chariots' static stresses and deformations, different static configurations of the chariot will be simulated. In this section, loads acting on the chariot will be described.

As explained before, Egyptian war chariots were usually ridden by two persons. Contrary to what most people think, Ancient Egyptians weight and height was not very different from the current population's average. Therefore, the weight and height of both the charioteer and the spearman will be like the current averages. Table 9.1.1 shows the values of the loads applied to the chariot.

Mohamed Moustafa, conservator at the Grand Egyptian Museum, shared the lightest of Tutankhamun's chariots weighed about 60-70 kg. This chariot is apparently the simplest one as it is formed only by the wood structure and was not covered with gesso and gilded layers.

No information could be found about the acceleration of the pull of the horses. Finally, 2m/s^2 was thought to be a reasonable acceleration.

LOADS and ACCELERATIONS	
Load due to the weight of a charioteer (P)	687,5 N
Force of the pull of the horses (F_h)	410 N
Acceleration of the pull of the horses (a)	2 m/s^2
Weight of a charioteer (m)	70 kg
Height of a person (H)	1,70 m
Gravity (g)	9,81 m/s^2
Weight of the chariot (M)	65 kg
Medium speed (v_m)	5,6 m/s
Maximum speed (v_{max})	14 m/s
Frictional coefficient between wood and sand (μ)	0,7
Frictional coefficient between different greased parts made of wood (f)	0,1
Pull of a person (F_p)	28 N

Table 9.1.1. *Loads, accelerations and weights applied to the chariot*

$$P = m \cdot g = 70 \cdot 9{,}81 \approx 687{,}5\ N$$

Equation 9.1.1. *Weight of one charioteer*

$$F_h = (2 \cdot m + M) \cdot a = 410\ N$$

Equation 9.1.2. *Horses' pull force*

$$F_p = 0{,}2 \cdot m \cdot a = 28\ N$$

Equation 9.1.3. *Person's pull force*

9.2. General Boundary Conditions

Unions between elements are not easy to implement. Therefore, only the axle and the wheels will be simulated separately. Later, the chariot is simulated as a complex.

The boundary conditions applied to the chariot in all the simulations are:

- Standard Earth gravity (9,81 m/s^2) in the -Y direction
- Remote displacement in the contact of the wheel with the ground. One of the wheels has a fix displacement in the X, Y and Z direction. The other wheel has been fixed in the X and Y direction. No rotations have been fixed on the wheels.
- Fixed vertical displacement on the upper part of the pole, where the yoke is positioned. This fixation represents the contact with the horses.
- The contact between the pole and the U-shaped socket will be a friction contact with a frictional coefficient of 0,2.
- The contact between the wheels and the axle will also be a frictional contact with a frictional coefficient of 0,2.
- Every other contact is a bonded contact.

Different configurations of the chariot will be studied to determine its behavior in different situations. The position of the wheels will be changed, studying the most vulnerable position, with the spokes open facing the ground, and the strongest position, with the spoke facing the ground vertical.

9.3. Previous Calculations

The floor of the chariot was made of leather, which is a very flexible material, therefore, it will not be a part of the structure of the model to be simulated. However, since the weight of the charioteers was centered in the leather floor, the reaction forces to the rest of the structure must be calculated. Not only the axle received part of the weight, the pole also received a percentage of it. To calculate the percentage of the weight that is distributed to every part, the floor of the body will be treated as a beam with three supports. In this case, only the forces corresponding to the charioteers standing will be considered (Figures 9.3.1 and 9.3.2). No pull forces are considered in this section as they do not act on the axle.

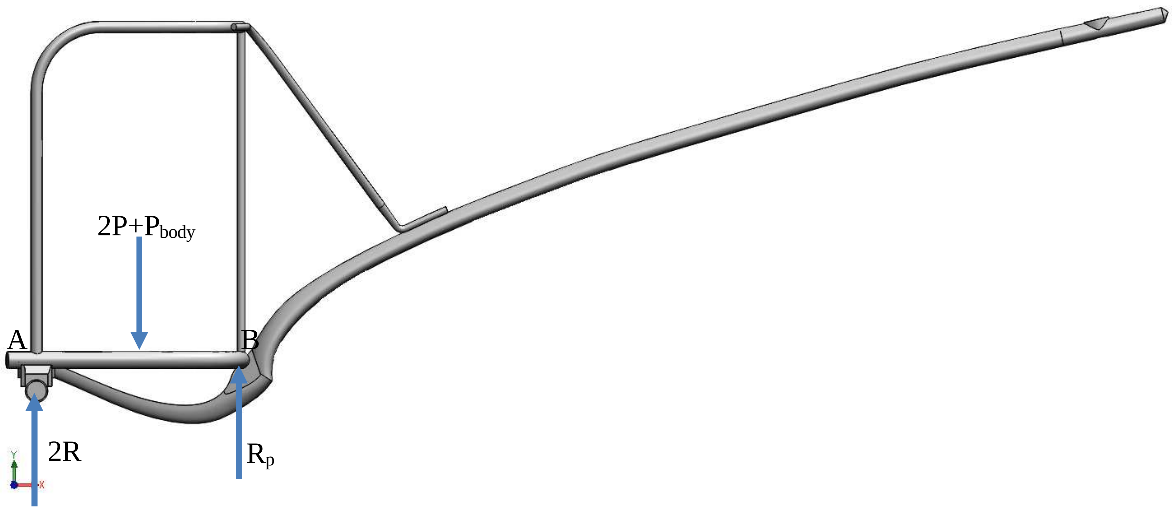

Figure 9.3.1. Free body diagram of the body and the pole when the charioteers are standing on it.

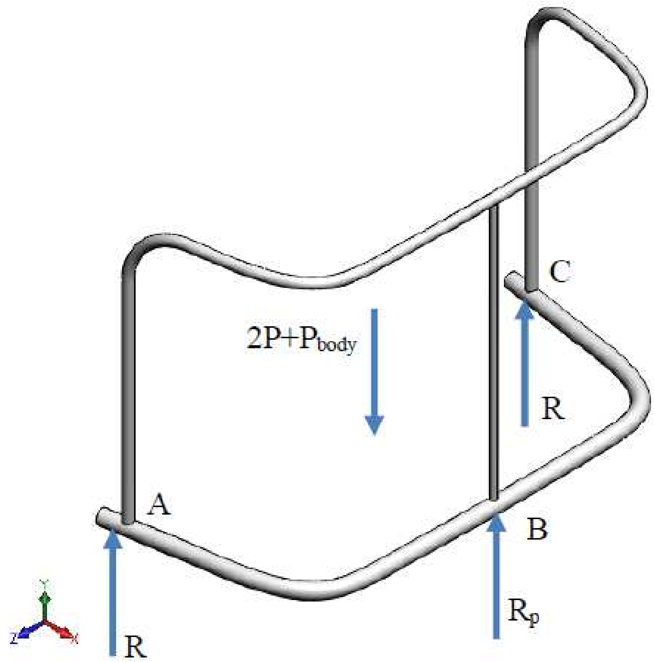

Figure 9.3.2. Free body diagram of the body of the chariot when the charioteers are standing on it.

Since the chariot is symmetrical, it can be assumed the two reaction forces of the body with the axle are equal. The weight of the body will be considered of about 25 kg. The length between A and B is 1 meter and the depth of the body floor is 0,46 meters. Considering this situation in equilibrium, the reaction force transmitted to the pole would be:

$$\sum F_y = 0 \rightarrow 2R + R_p = 2P + P_{body}$$

$$\sum M(A) = 0 \rightarrow -(2P + P_{body}) \cdot 0{,}23 + R_p \cdot 0{,}46 = 0$$

$$R_p = P + \frac{P_{body}}{2} = 810\ N$$

$$R = \frac{P}{2} + \frac{P_{body}}{4} = 405\ N$$

9.4. Axle and Wheels

It is interesting to study the axle and wheels separately, because it allows a more accurate analysis of the wheels. Wheels were not affected by the horses' pull as they rotated. However, they were affected by the charioteers' and the cabin's weight.

Tutankhamun's chariot wheels are one of the most interesting parts of the chariots. Their construction is remarkable and was one of the parts that made the chariot a powerful and strong weapon.

The axle works as a beam supported vertically by the wheels (wheel track 1,8 m) and receives the forces calculated in the previous section. As stated before, while the chariot was being ridden, the two charioteers stood on the leather floor. Given the fact the axle was not placed in the middle plane of the body but on the rear end, it allowed a more comfortable ride for the charioteers as they were not standing directly on the axle receiving all the ground impacts. However, this positioning of the axle meant the horses received extra weight from the charioteers. The body's load distribution was the following (Figure 9.4.1):

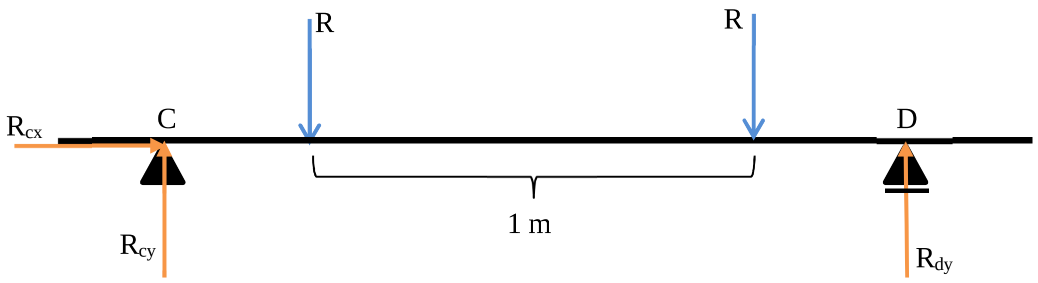

Figure 9.4.1. *Configuration 1 of the axle.*

$$\sum M(C) = 0 \rightarrow -R \cdot 0{,}4 - R \cdot 1{,}4 + R_{dy} \cdot L = 0 \rightarrow R_{dy} = R = 405\ N$$

$$\sum F_x = 0 \rightarrow R_{cx} = 0$$

$$\sum F_y = 0 \rightarrow R_{cy} + R_{dy} = 2R \rightarrow R_{cy} = 2R - R = R = 405\ N$$

9.4.1. Axle's Section Efforts

Section AB: $N = 0$

$T = R = 405\ N$

$M = R \cdot x$

Section BC: $N = 0$

$T = 0$

$M = R \cdot x - R \cdot (x - 0{,}4) = R \cdot 0{,}4 = 162\ Nm$

Section CD: $N = 0$

$T = -R = -405\ N$

$M = R \cdot 0{,}4 - R \cdot (x - 1{,}4) = R \cdot 1{,}8 - R \cdot x$

The critical section is the middle section, especially the middle part of the axle, where the maximum bending occurs as well as the maximum deformation.

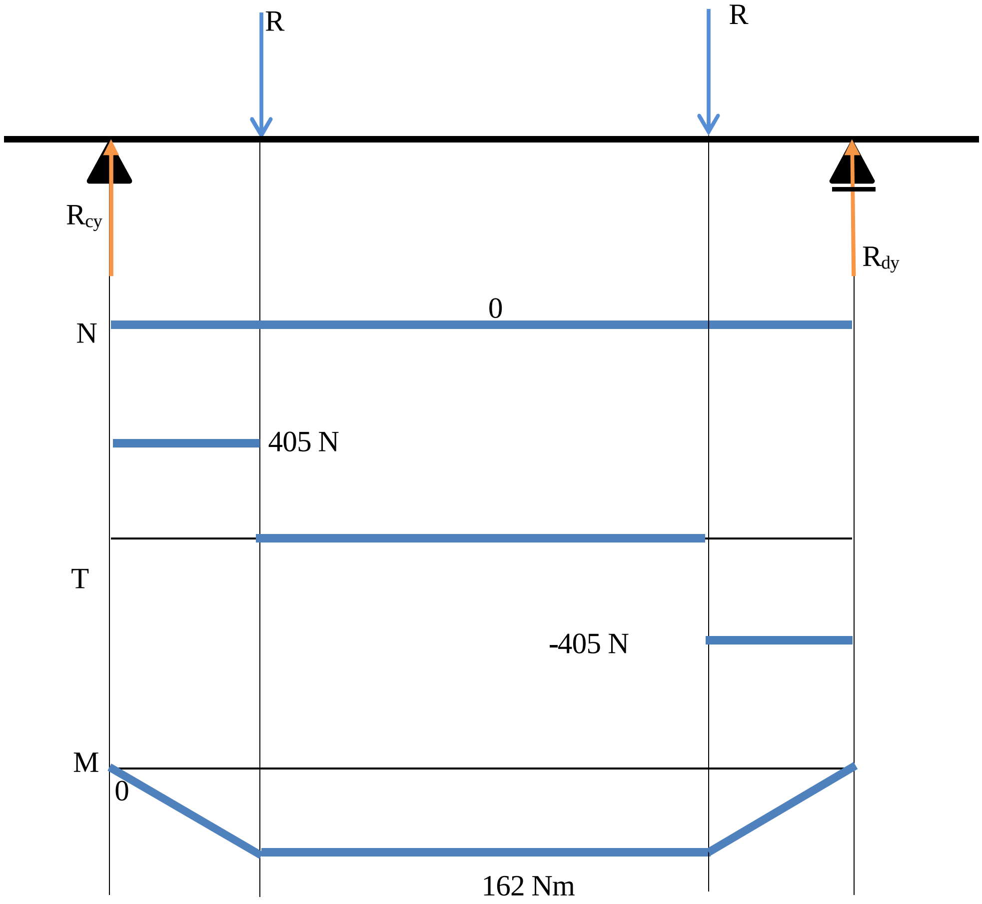

Figure 9.4.2. Section efforts diagram.

9.4.2. Axle Maximum Displacement

To calculate the maximum displacement of the axle Castigliano's method will be used. As stated in section 8.3.1 the formula is as follows:

$$\delta = \int_0^l \left(\frac{N_x}{EA}\frac{\delta N_x}{\delta P} + \frac{T_y}{GA_1}\frac{\delta T_y}{\delta P} + \frac{M_x}{EI_x}\frac{\delta M_x}{\delta P} + \frac{M_y}{EI_y}\frac{\delta M_y}{\delta P} + \frac{M_z}{EI_z}\frac{\delta M_z}{\delta P} \right) dx$$

Equation 9.4.1. Castigliano's method

This formula can be simplified as it can be studied as a 2D model, resulting in the following formula:

$$\delta = \int_0^l \left(\frac{N}{EA}\frac{\delta N}{\delta P} + \frac{T}{GA_1}\frac{\delta T}{\delta P} + \frac{M}{EI_Z}\frac{\delta M}{\delta P} \right) dx$$

Equation 9.4.2. Castigliano's method for 2D studies

For the axle's circular section of constant diameter d = 50 mm:

$$I_Z = \frac{\pi \cdot d^4}{64} = \frac{\pi \cdot 50^4}{64} = 306796\, mm^4$$

$$A = \pi \cdot \frac{d^2}{4} = 625\pi = 1963{,}5\, mm^2$$

$$A_{1\, circular} = \frac{9}{10} \cdot A = 1767{,}15\, mm^2$$

$$G = \frac{E}{2 \cdot (1+\nu)} = \frac{10780}{2 \cdot (1+0{,}4)} = 3850\, MPa$$

This formula is valid when the load is applied to the point where the displacement needs to be known. In this case, the middle section of the axle has no load applied to it. Therefore, this formula needs to be adjusted using the unitarian force method, which consists in applying a unitarian force to the point of interest. The adjusted formula for the displacement is:

$$\delta = \int_0^l \left(\frac{N}{EA} N^1 + \frac{T}{GA_1} T^1 + \frac{M}{EI_Z} M^1 \right) dx$$

Equation 9.4.3. *Unitarian force-adjusted Castigliano's method*

Where N^1, T^1 and M^1 are the section efforts created by the unitarian force. To study the unitarian force another diagram is needed (Appendix C).

The axle will be divided into four parts to calculate the displacement in the middle section (E).

$$\delta_{CA} = \int_0^{400} \left(0 + \frac{R}{G \cdot A_1} \cdot 0{,}5 + \frac{R \cdot x}{EI_Z} \cdot 0{,}5x \right) dx = 1{,}32\, mm$$

$$\delta_{AE} = \int_{400}^{900} \left(0 + 0 + \frac{R \cdot 400}{EI_Z} \cdot 0{,}5x \right) dx = 7{,}96\, mm$$

$$\delta_{EB} = \int_{900}^{1400} \left(0 + 0 + \frac{R \cdot 400}{EI_Z} \cdot (-0{,}5x + 900) \right) dx = 7{,}96\, mm$$

$$\delta_{BD} = \int_{1400}^{1800} \left(0 + \frac{-R}{G \cdot A_1} \cdot (-0{,}5) + \frac{R \cdot 1800 - R \cdot x}{EI_Z} \cdot (-0{,}5x + 900) \right) dx = 1{,}32\, mm$$

$$\delta_E = \delta_{CA} + \delta_{AE} + \delta_{EB} + \delta_{BD} = 18{,}56\, mm = 0{,}01856\, m$$

Wheels' position changes according to the spokes' positioning towards the ground. In their weakest position, the spokes are open facing the ground. The strongest position corresponds to the vertical position of the spokes facing the ground.

9.4.3. Configuration 1: Open Spokes facing the Ground

This is the wheels' weakest position as the felloe's deformation is greater. The open position of the spokes allows a greater deformation of the felloe.

Two vertical forces of 405 N have been applied on the cradles, which is the union between the body and the axle. The boundary conditions are the same as in section 9.2.

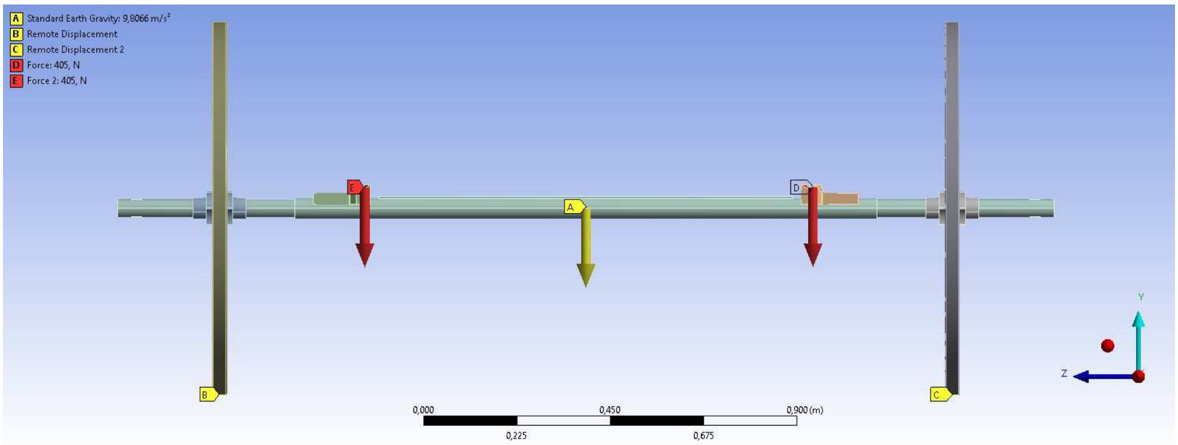

Figure 9.4.3. Configuration 1 boundary conditions

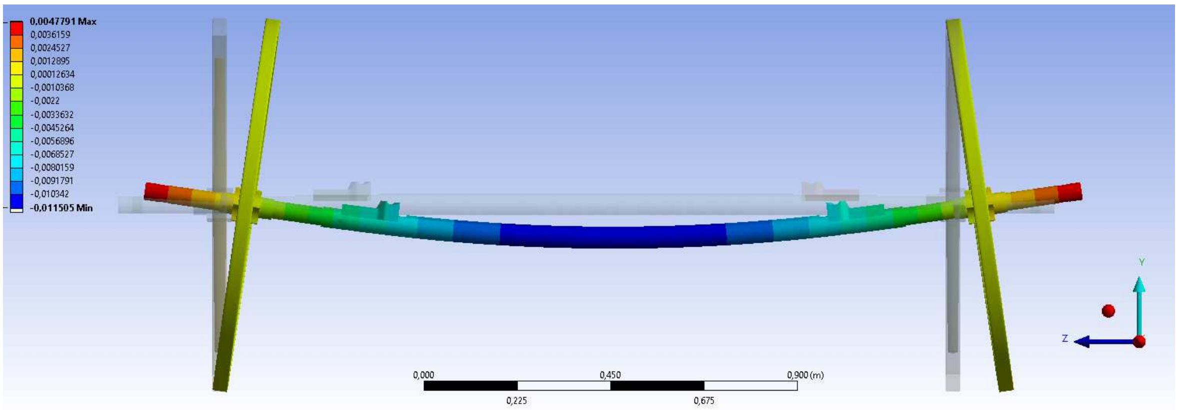

Figure 9.4.4. Vertical deformation (Y direction) for Configuration 1

The maximum vertical deformation occurs in the axle's middle plane and has a value of 12 mm. This value is close to the one calculated by Castigliano's method. The differences between the two values are due to the axle's changing section, which is pear-shaped in its middle section. In Figure 9.4.4, it can be seen wheels slightly rotate in the X axis due to the moment created by the charioteers' weight. Due to this rotation, wheels move a maximum of 18 mm in the Z axis.

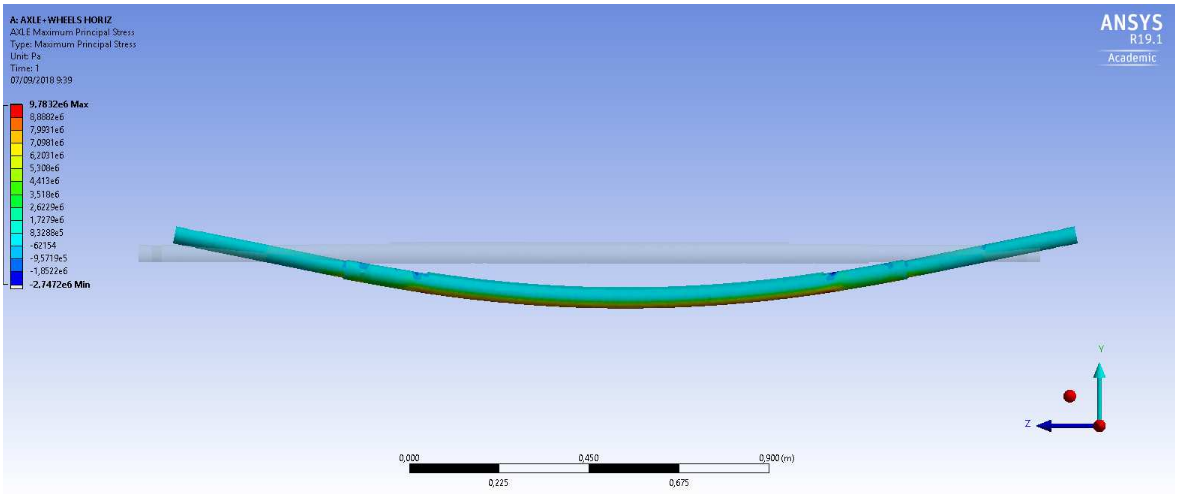

Figure 9.4.5. *Axle's maximum principal stresses*

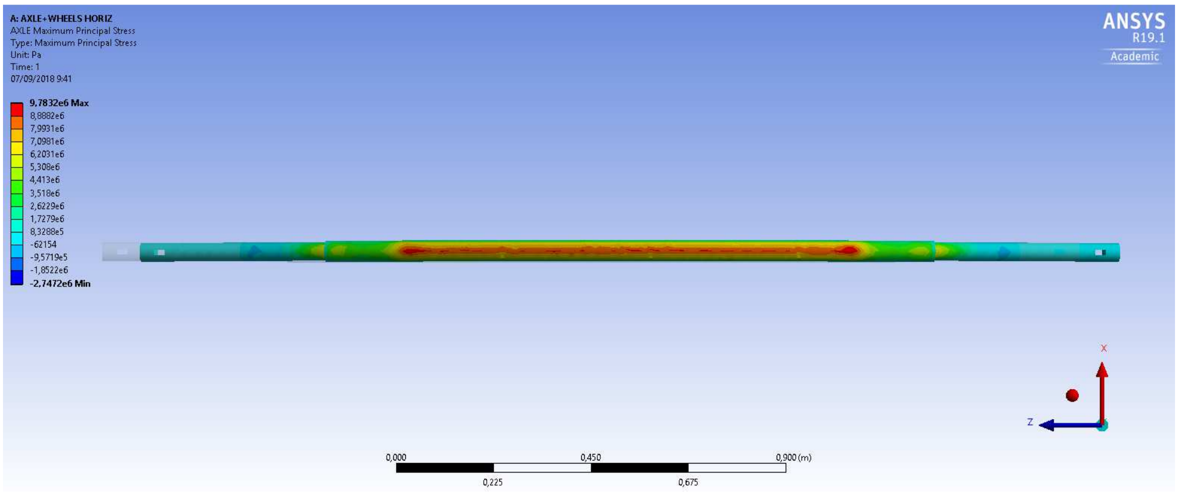

Figure 9.4.6. *Axle's maximum principal stresses (bottom view)*

The axle's maximum principal stress occurs in its middle plane at the bottom part and has a value of 9,72 MPa (see Figures 9.4.5 and 9.4.6). This is a very low value if compared to elm's tensile yield strength of 78 MPa. By maximum stress criterion, which states that a material's safe region is $\sigma_t > \sigma_1$, it can be assumed that the axle is not near failure.

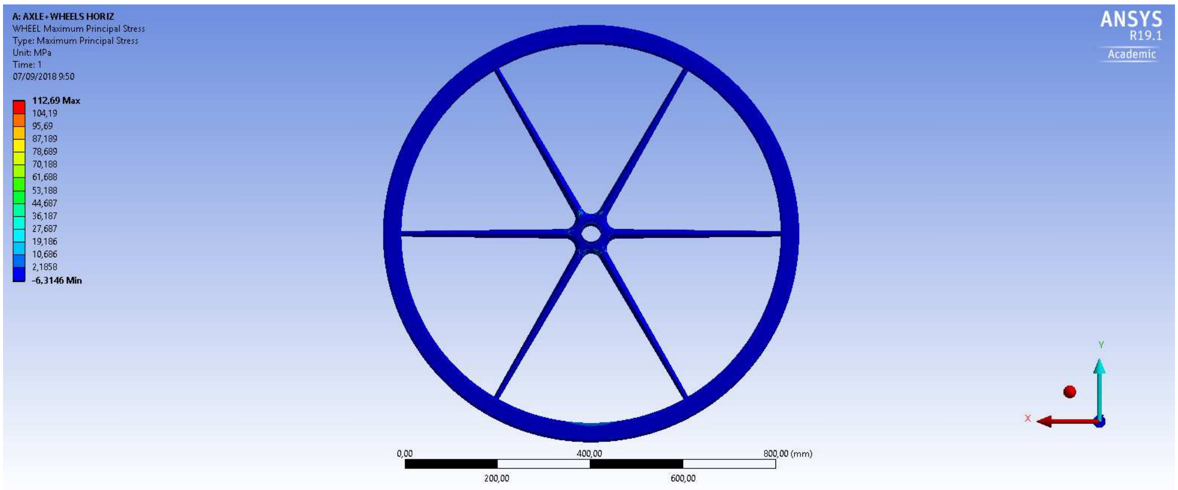

Figure 9.4.7. Wheel's maximum principal stresses

The wheel's maximum stress is 112,69 MPa. This value is outside the safe region in the maximum principal stress criterion. However, these high values occur in the wheel's hub, and the other parts of the wheel shows even stresses (Figure 9.4.7). This could lead to think the wheel was likely to fail because of the hub. Nevertheless, this part of the wheel was strengthened by raw-hide linings, gesso and sometimes gold. Because these reinforcement layers have not been simulated, it cannot be stated the wheels did or did not fail because of these parts, although it is likely the extra layers provided enough strength for the wheels not to break by the hub.

If the hub is excluded from the stress analysis, wheels show high tensions in the spokes' inner part which was also reinforced. Still, the maximum stress value is 27 MPa which is in the failure criterion safe region (see Figure 9.4.8). The felloe shows its higher tensions in its bottom part of 4 MPa.

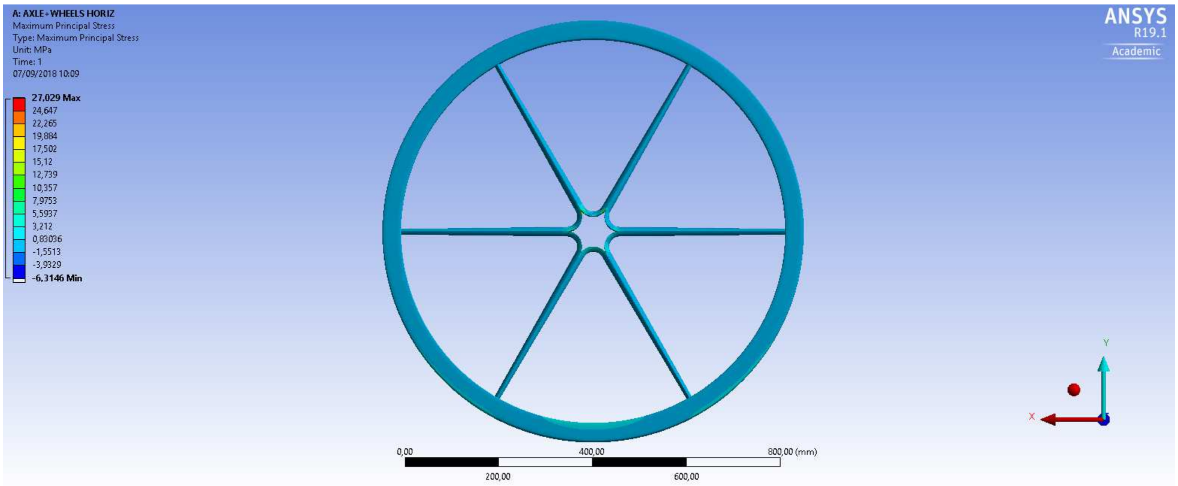

Figure 9.4.8. Wheels' maximum principal stresses (no hub)

9.4.4. Configuration 2: Vertical Spoke

This configuration does not allow great deformations on the felloe since the vertical spokes act as vertical beam under compression and bending moment. Thus, not allowing the felloe to deform in the bottom part.

The boundary conditions and forces applied are the same as in Configuration 1. However, the position of the spokes has been changed.

For this configuration, the maximum vertical displacement occurs in the axle and has a value of 11 mm, similar to Configuration 1. Again, wheels show rotation in the X axis due to moments created by loads. Their displacement in the Z axis is 17,9 mm (like Configuration 1).

The axle's maximum principal stress is 9,62 and occurs in its middles section, as in Configuration 1 (see Figure 9.4.9).

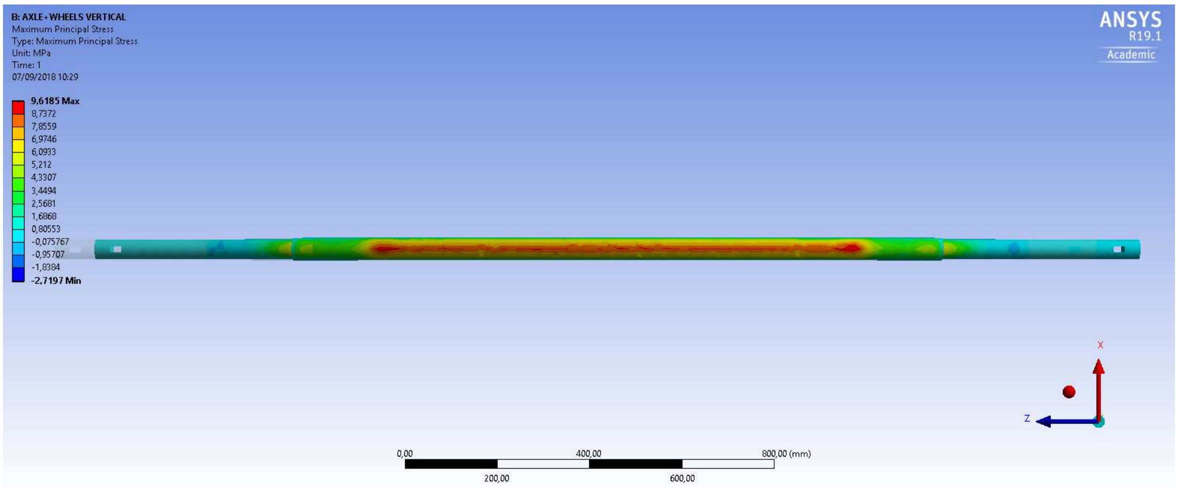

Figure 9.4.9. Axle's maximum principal stresses (bottom view)

As happens in Configuration 1, the wheel's maximum stress occurs in the hub and has a greater value than the tensile yield strength, which indicates failure. However, as stated before, reinforcement layers were applied. When the hub is excluded from the stress analysis, a maximum principal stress of 21,38 MPa occurs in the spokes' inner part, as seen in Figure 9.4.10.

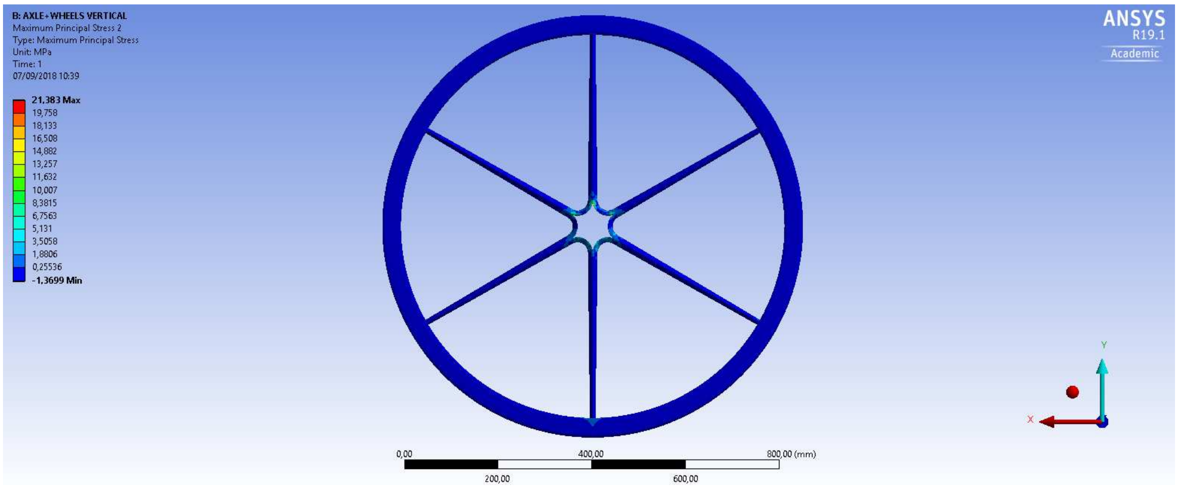

Figure 9.4.10. *Wheel's maximum principal stresses (no hub)*

Table 9.4.1 is a comparison between the axle and wheels' configurations:

Comparison between Configuration 1 and Configuration 2		
	Configuration 1	**Configuration 2**
Axle's maximum vertical deformation	12 mm	11 mm
Axle's maximum principal stress	9,72 MPa	9,62 MPa
Wheel's maximum principal stress	27 MPa	21,38 MPa
Hub's maximum principal stress	112,69 MPa	150,99 MPa

Table 9.4.1. *Comparison table between axle and wheels' Configurations*

9.4.5. Maximum Load Supported by the Axle and the Wheels

As stated in the previously, the axle and wheels were in the safe region of the stress criterion, which means the complex was far from failing when the normal loads were applied. In this section, more load will be applied to the complex to determine how much load it could bear. For this simulation, Configuration 1 will be used, and the forces applied to the complex will be magnified.

After several trials, simulation showed wheels could bear up to 3 times the weight of the body and the charioteers without breaking. Although the axle can support more than six people, simulation shows maximum principal stress for the wheels is 79,55 MPa, which technically exceeds elm's tensile yield strength. As happened in Configuration 1, the hub shows high stresses but, as explained before, these stresses might be unrealistic due to the lack of knowledge of precision on the hub's measures and the lack of the reinforcement layers. However, as explained before, this part of the wheels was reinforced with raw-hide linings, which strengthened this part. This means the chariot could support up to 3 times its weight.

In this case, the axle's maximum vertical deformation and maximum principal stress would be 33 mm (Figure 9.4.11) and 28,9 MPa (Figure 9.4.12), which means the axle would allow more weight on top. The wheels' maximum principal stress is 79,55 MPa (Figure 9.4.13).

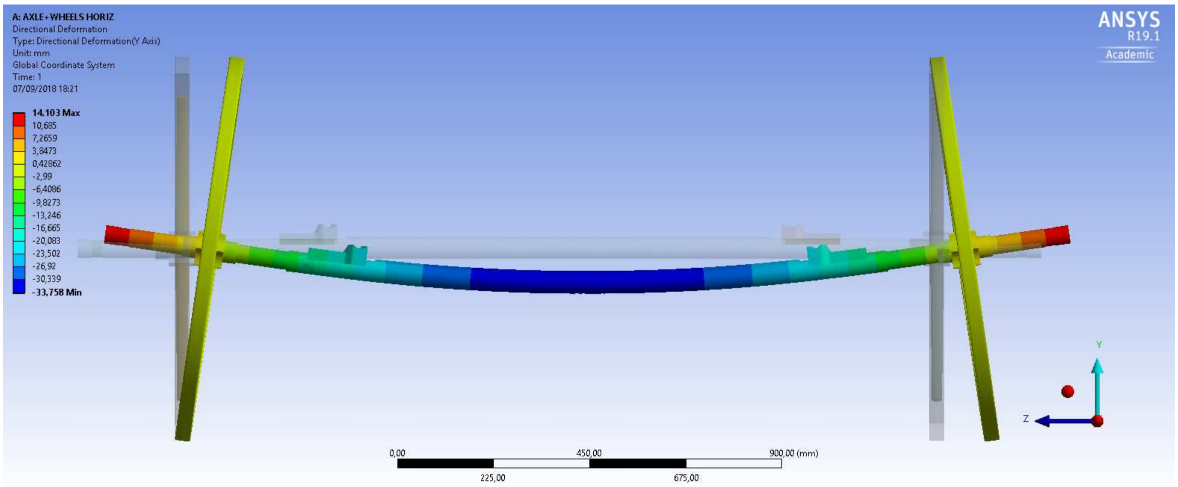

__Figure 9.4.11.__ Axle and wheels' vertical deformation

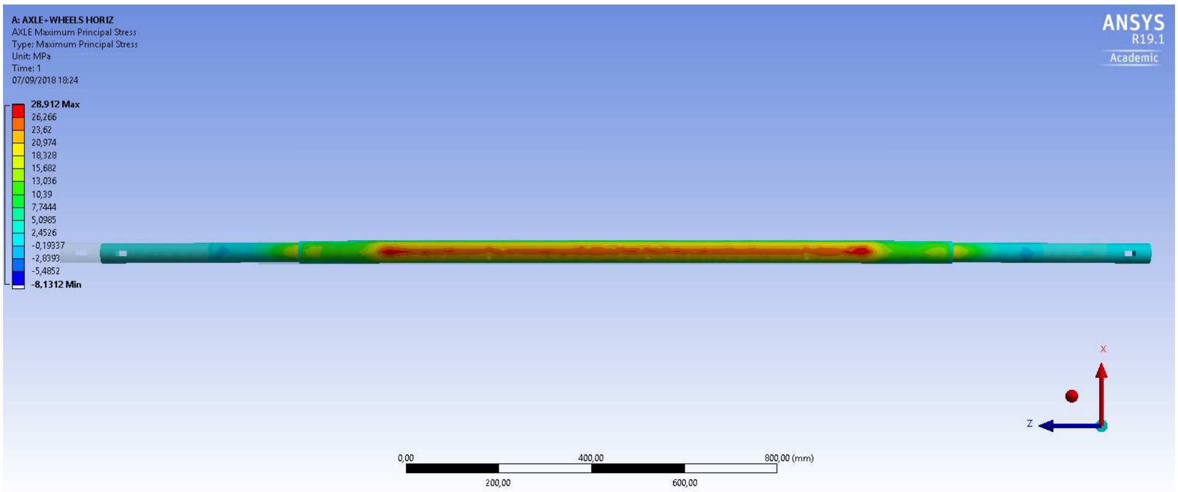

__Figure 9.4.12.__ Axle's maximum principal stresses

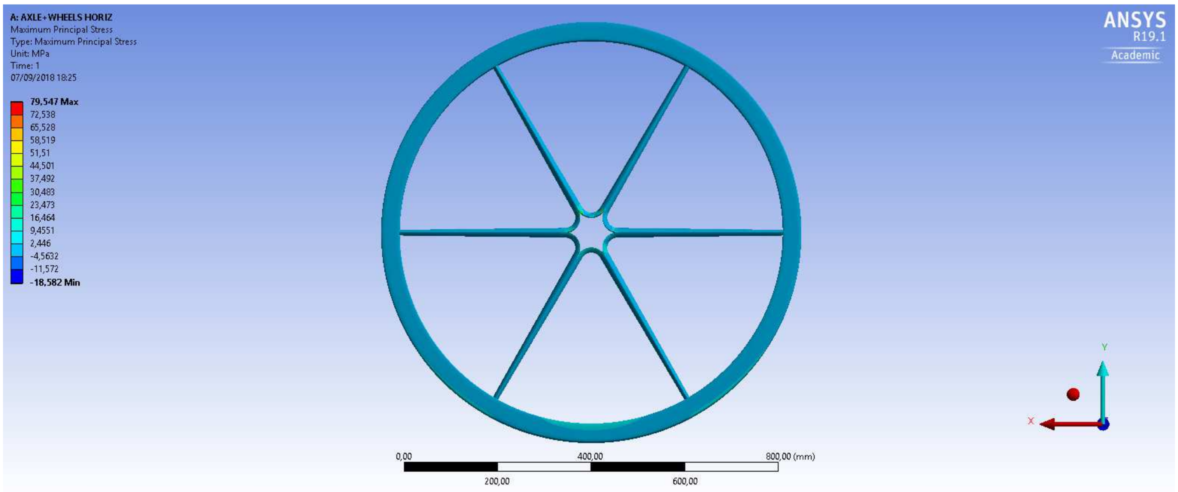

Figure 9.4.13. *Wheels' maximum principal stresses*

The fact wheels could bear up to 3 times the normal weight, does not mean they were over dimensioned. When the chariot went over a pothole, it could experiment a 2 or 3 g increase, which means the chariot should be able to support 2 to 3 times the normal weight. According to these simulations, the chariot was apt to support this weight.

9.5. Body Simulation

The body, pole and axle will be simulated together to determine the deformations and static stresses the body and the pole undergo. When simulating all the chariot, and the unions were defined properly, the wheels were deformed in unrealistic ways. At the same time, when applying inertia relief to the structure, contacts between parts could not be defined properly and unrealistic deformation occurred as well. Therefore, it was chosen to simulate the chariot in two smaller complexes; the axle and wheels as one complex, and the axle, pole and body as another complex.

9.5.1. Traction

The pole was mostly subjected to traction forces due to the pull of the horses. Its geometry was quite complex, as explained in previous sections. Its section was a pear-shaped section, similar to a teardrop, that changed constantly. It began with a narrower section and widened towards its union with the body of the chariot.

As stated before, the axle was fixed to the body of the chariot which means it did not rotate freely. Because the axle was placed in the rear part of the body structure, when the charioteers were standing on the floor of the chariot, part of the weight fell directly to the pole. This meant the pole did not only receive a traction force from the horses, but also received part of the weight of the charioteers. This meant a more comfortable ride for the charioteers and placed some of their weight directly on the horses.

For this configuration, a traction force (F_h) of 410 N will be applied in the X axis to the pole, two vertical forces of 405 N (R) will be applied to the unions between the axle and the body and a vertical force will be applied to the union between the pole and the body (R_p). To simulate a person's pull force (F_p), two 28 N forces will be applied to the body front sidings. Boundary conditions and forces applied to the body, pole and axle can be seen in Figure 9.5.1.

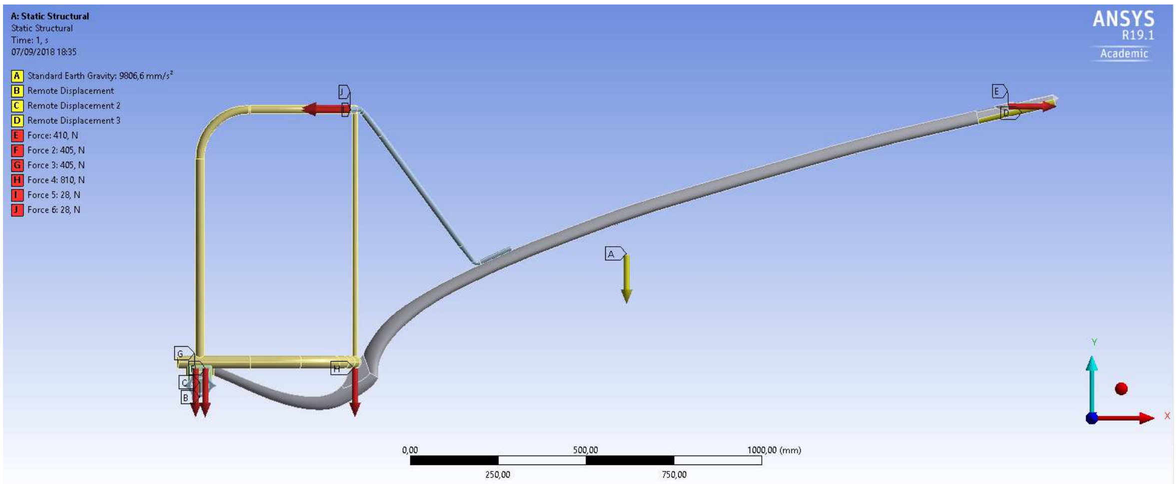

Figure 9.5.1. Boundary conditions and forces applied to the body, pole and axle.

Since the axle has already been studied in previous sections, section 9.5 will only focus on the chariot's pole and body.

9.5.1.1. Body

When the charioteers were standing on the chariot, the floor surface was inclined. Therefore, the body structure was inclined, loading the horses with more weight, as can be seen in Figure 9.5.

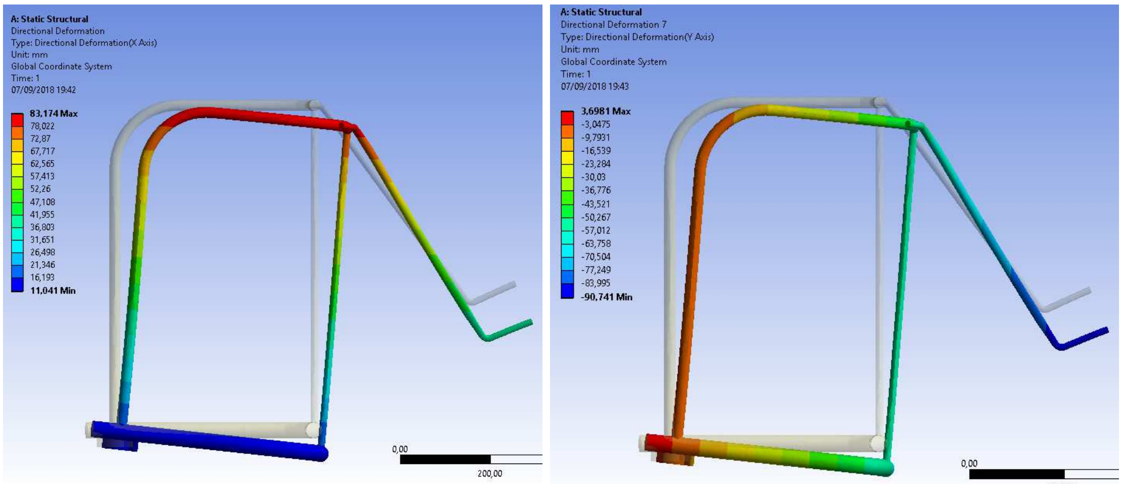

Figure 9.5.2. Body's inclination due to the charioteer's weight. Left X axis. Right Y axis

It can be seen the body's maximum displacement in the X axis (Figure 9.5.2, left) occurs in the front sidings and has a value of 83 mm. this means the body would incline towards the horses and allow a support for the charioteers to stand more comfortably. On the other hand, the maximum vertical deformation, which is 58 mm, occurs on the front bar (Figure 9.5.2, right). Deformations in the Z axis are negligible.

The body's maximum principal stresses occur in the rear siding bars and the two front bars and have a value of 31,2 MPa, as seen in Figure 9.5.3. This value fits into the maximum principal stress' safe region, which indicates the body did not go into failure under normal circumstances.

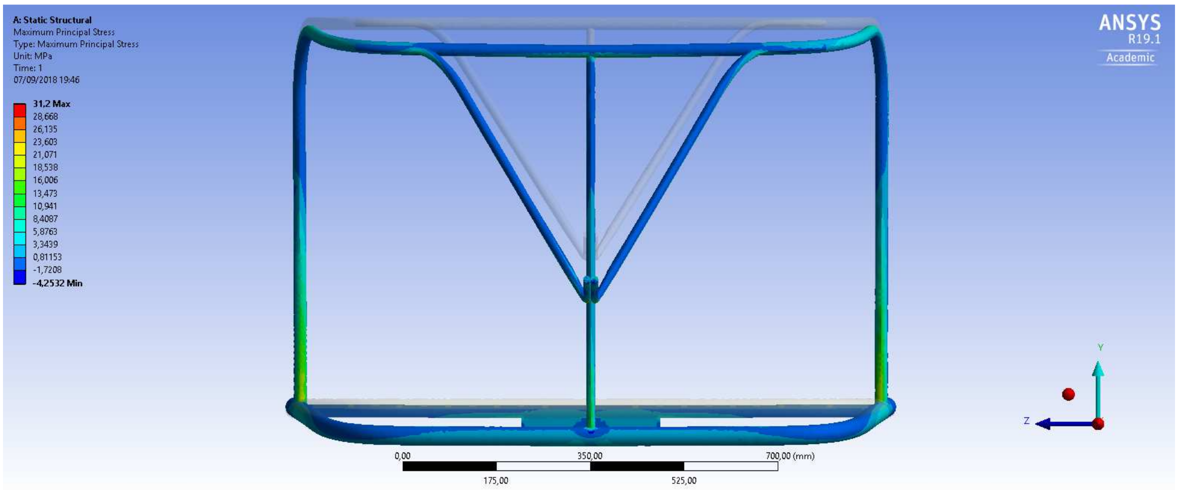

Figure 9.5.3. *Body's maximum principal stresses*

9.5.1.2. Pole

As explained before, when the charioteers were standing on the chariot, its body inclined. This made the pole stretch even more, as the union between the pole and the body moved down in the vertical direction.

Figure 9.5.4 and Figure 9.5.5 show the pole's directional deformation in the X and the Y direction, respectively. The deformation in the Z direction is not relevant in this case as it is negligible. X and Y maximum deformation are 40 mm and 95 mm respectively. Both maximums occur in the pole's middle section, which as can be seen in both Figures, is the most deformed part.

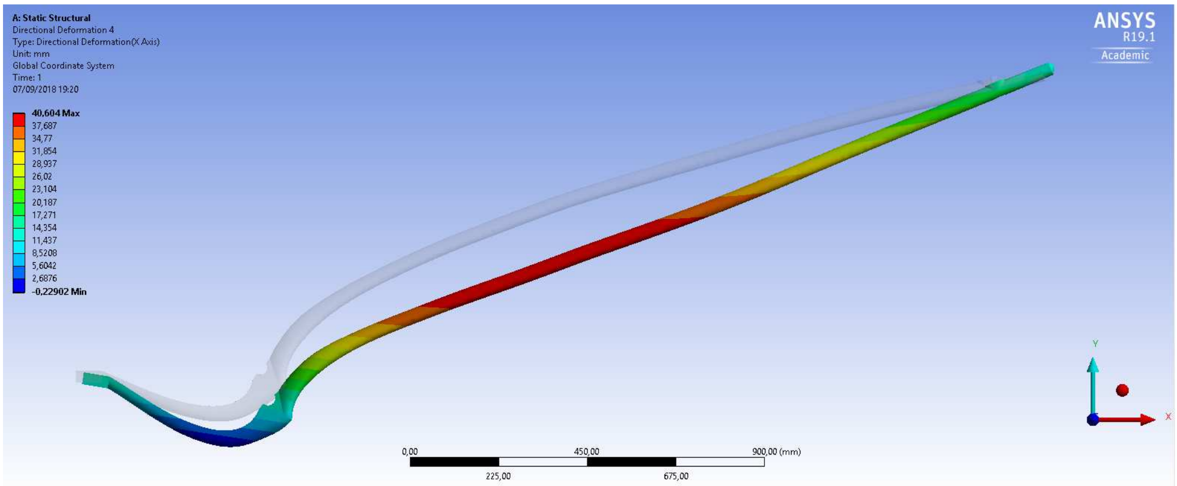

Figure 9.5.4. Pole's deformation in the X direction

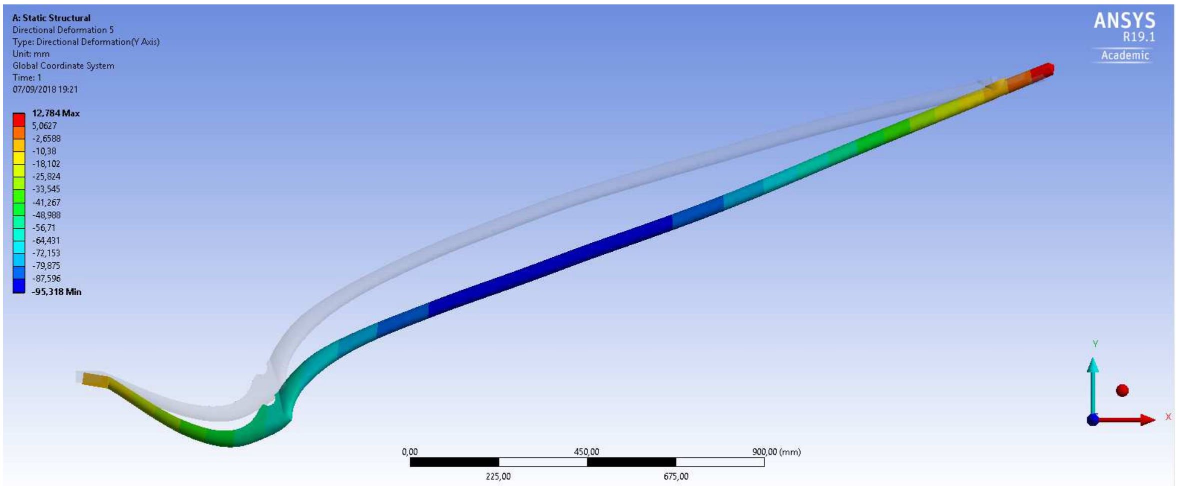

Figure 9.5.5. Pole's deformation in the Y direction

As can be seen in Figure 9.5.6, the pole's maximum principal stresses occur near the union between the pole and the body and in the middle section, as well. This is a very curved part of the pole that suffers the most structurally. This part of the pole receives a traction force on both sides, one being the pull from the horses, the other being a part of the charioteers' weight. The maximum principal stress is 35,9 MPa (Figure 9.5.6), which complies with the maximum principal stress criterion.

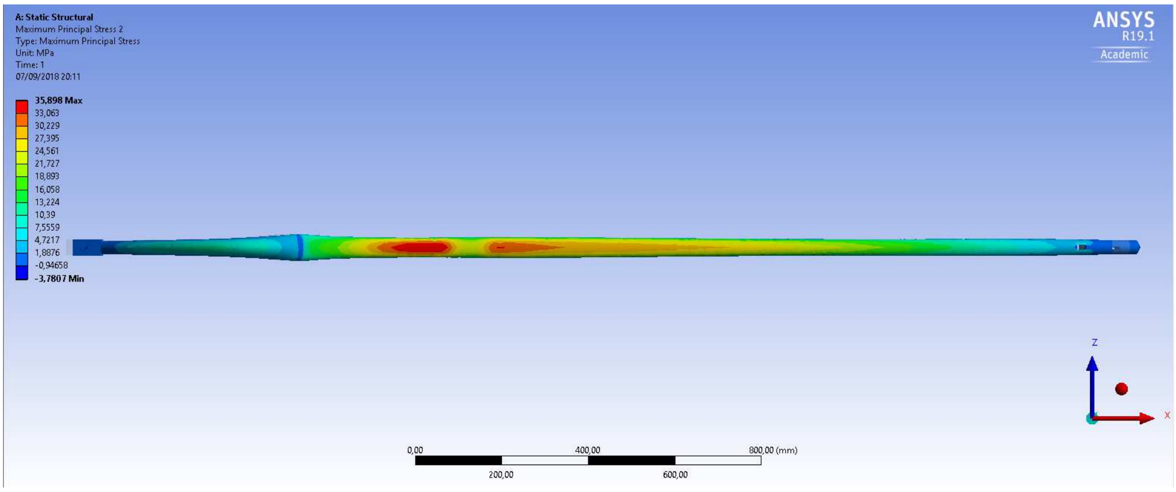

Figure 9.5.6. *Pole's maximum principal stresses (bottom view)*

9.5.2. Torsion

The pole was not only subjected to traction loads. Due to soil imperfections and the trot of the horses, the pole also suffered torsion forces. Doctor Bela I. Sandor commented that a torsion up to 10° would be an acceptable and realistic degree of torsion for the pole.

The boundary conditions (see Figure 9.5.7) are the same as in part 9.5.1, although a torsion of 10° has been added to this configuration as well. It is interesting to see the behavior of the pole when subjected to both traction and torsion.

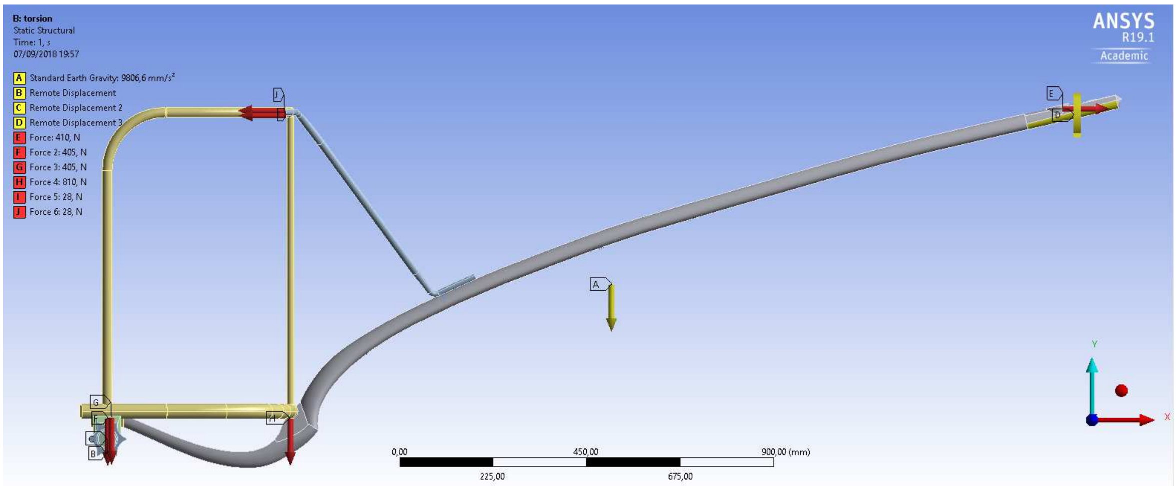

Figure 9.5.7. *Torsion and traction boundary conditions for body, pole and axle*

9.5.2.1. Body

Displacements in the X, Y and Z direction are 80 mm, 89,67 mm and 4 mm respectively. Maximum principal stresses are 57,71 MPa and occur in the front bars and rear bars of the siding. The deformation is similar in shape to the one in part 9.5.1.1.

9.5.2.2. Pole

The study of the pole is more interesting for this configuration because a torsion of 10° has been added to the simulation. In this case, X and Y deformations are like deformations in part 9.5.1.2. However, Z deformation is larger in this case due to the torsion. Maximum deformation in Z axis is 29,34 mm and it occurs in the yoke's end of the pole, as seen in Figure 9.5.8.

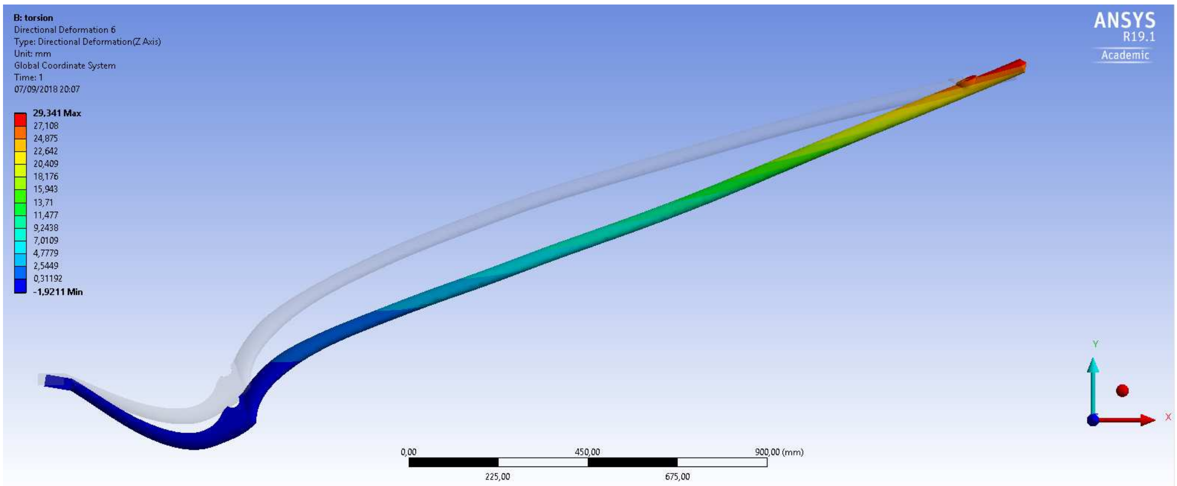

Figure 9.5.8. Pole's Z deformation

Maximum principal stresses values do not change much either, the highest stress is 36,9 MPa. However, placement has been moved slightly to one side (Figure 9.5.9). The higher the torsion is, the more displaced would be the stresses.

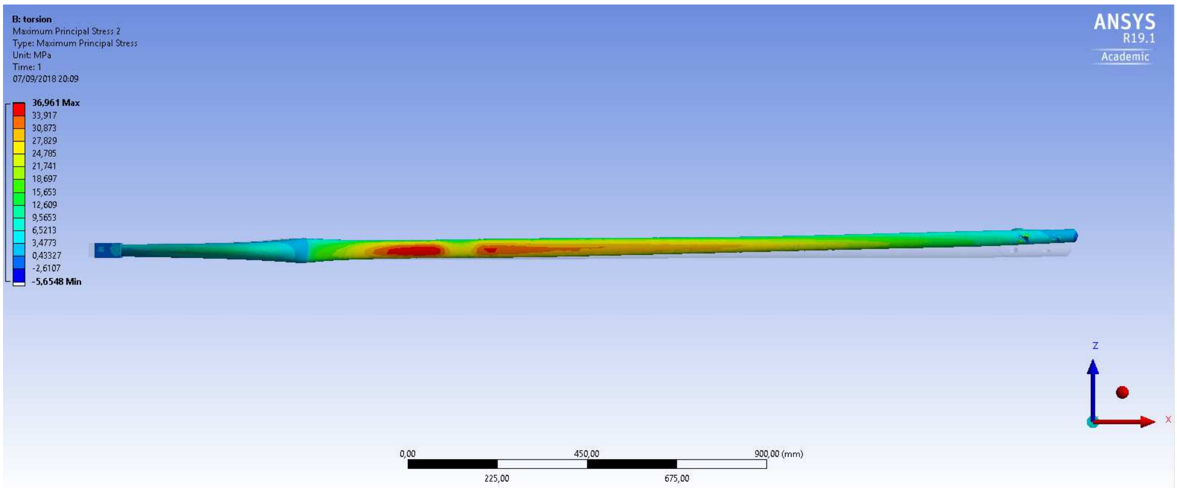

Figure 9.5.9. Pole subjected to torsion maximum principal stresses (bottom view)

10. Rollover Stability

One of the characteristics of these chariots was the difficulty they had to overturn. As they have such a wide wheel-track, it is thought that it was very difficult for them to rollover, even when performing very tight curves. To prove this theory, the acceleration of the overturn of the chariot was calculated with the following formula:

$$a_y = \frac{g \cdot b}{2 \cdot Y_{CdG}}$$

Where:

- g: gravity (m/s^2)
- b: wheel track (m)
- Y_{CdG}: Height of the center of gravity of the complex chariot + charioteers (m)

To calculate the height of the center of gravity of the chariot with the two charioteers on top of it the Method of Composite Parts was used. The center of mass of the chariot was determined by means of the tools in SolidWorks because of the complicated geometry of it. The center of gravity in a man's body is positioned at 57% of its height (from the ground). For the acceleration formula only the height of the center of gravity of each body was needed. As stated in the previous sections, the average height of an Egyptian man is about 1,70 m with a weight of 70 kg. The following table shows the height of the center of gravity of the bodies:

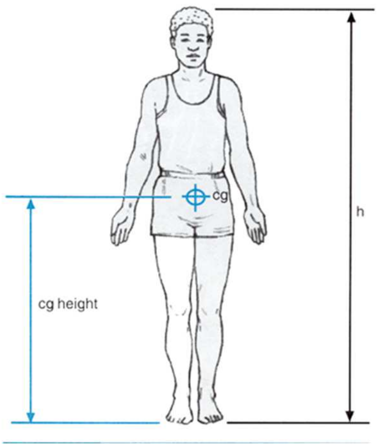

Figure 9.5.1. *Position of the center of a gravity of a man.*

HEIGHT OF THE CENTER OF GRAVITY	
Chariot	0,575 m
Charioteer	0,969 m
Chariot + 2 Charioteers	1,15 m

Table 9.5.1. *Height of the center of gravity of the chariot.*

Since the two charioteers are on top of the chariot (at 0,45 m above the ground) the formula is the following:

$$Y_{CdG} = \sum \frac{m_i \cdot y_i}{m_i} = \frac{65 \cdot 0{,}575 + 2 \cdot 70 \cdot (0{,}969 + 0{,}45)}{65 + 2 \cdot 70} \approx 1{,}15\ m$$

Therefore, the overturn acceleration would be:

$$a_y = \frac{9{,}81 \cdot 1{,}8}{2 \cdot 1{,}25} = 7{,}0632 \ m/s^2$$

The result of the acceleration is so high that it obviously could not be reached. This result shows that the chariot was more likely to slide rather than to rollover. Given the friction coefficient of the ground and the acceleration needed to overturn, it can be stated that the chariot would almost never rollover in a moderately even ground, instead, it would slide.

11. Budget

Table 10.1.1 provides information about the expenses regarding the realization of this project. The table includes not only expenses due to licensing of software used for the modelling and simulation of the chariot but also personal expenses while making this project. As this project is purely academic, no payback is included.

Software and Resources		Price [€/year]
	SolidWorks license	0
	Ansys Mechanical license	250
	Ansys Academic license	0
	Computer	Own
	Microsoft Office license	149
		Total expenses [€]
		399

Table 9.5.1. *Software and resources budget*

Personnel costs		Price ([€/h] or [€] *)	Time [h]	Total [€]
	Research	15	168	2520
	3D Modelling	15	112	1680
	Simulating	15	260	3900
	Report	15	160	2400
Travel	Living expenses*	-	96	800
	Museum fees*	20	-	20
	Transport*	-	72	440
				Total expenses [€]
				11.760

Table 9.5.2. *Personnel costs budget*

Discussion

This project's realization has been the basis for the creation of new lines of research that are intended to be studied during the master thesis.

- Egyptian chariots were very fast and agile. To simulate the dynamics of the chariot would give an idea of their resistance in motion.

- One challenging area is the anti-roll system, which also worked as a spring-shock-absorbing system. Despite professor Bela I. Sandor's publications about this subject, he revealed it was a much more complex subject where important work can be done. There are many elements involved such as:
    - The U-shaped socket on the axle.
    - The D-bar, which plays a major role by warping out-of-plane when it resists the pole's twisting.
    - The vertical leather tenons that flexibly connect the rear floor bar to the axle.
    - The yoke system.

- The raw-hide and leather bindings were frictional and worked as energy-absorbing elements. Testing different raw-hide bindings and simulating them would be essential.

- To simulate the gesso and gold layers and how they affected the entire structure. This would allow to know if royal chariots would give the pharaoh any advantage in the face of private chariots or, if contrary, it would be a detriment for the pharaoh.

Conclusions

One of the main objectives of this project was to prove the high technology design of the chariot. After the simulations performed in this project, the chariots' design has proven to be intelligent and utilitarian, the resistance and durability of which are truly remarkable.

The resistance of the axle and the wheels proves the chariot would have been able to support three times more weight than it normally did. The axle's positioning in the chariot was also crucial for the commodity of the charioteers. Because it was positioned in the rear part of the cabin, the charioteers did not receive all the ground impacts directly and part of the charioteers' weight fell on the horses. The wheels' structure is an intelligent design that allowed stresses to distribute along two V-shaped spokes, which made the wheel more resistant and durable. Moreover, the elliptical shape of the section of the spokes made them more resistant to bending moments. The layers of raw-hide linings and gesso strengthened the wheels' inner part. The pole, which did not only work as a pull for the horses, was crucial for the ride's comfortability, as, along with the body, acted like a bow. Finally, the body, which was usually covered in leather or gesso and gold, provided a comfortable support for the charioteers and allowed them to battle on the chariot.

Therefore, it can be stated that Egyptian war chariots were not only breathtaking pieces of art, which even nowadays have the power of delighting numerous archaeologists, but they were also important weapons that brought clear weapon superiority to the Egyptian army for centuries. Professor Bela I. Sandor declared that a current engineer would not have designed the chariots better than an ancient Egyptian engineer with their same tools, and he was right.

After performing this study there is one thing that can be stated. Throughout time and humankind history, the only thing that persists and that makes humankind progress is curiosity, observation and effort.

Acknowledgements

I am most grateful to professor Bela I. Sandor, professor emeritus at College of Engineering in University of Wisconsin-Madison, for his inestimable help and guidance in the beginning of this project. He provided me with crucial information on where to find reliable chariot data and was kind enough to send me some of his reports and give me ideas to start this project, which helped me immensely. He has also provided me with new investigation lines to develop in future projects.

I would also like to acknowledge my professors, Lluís Roger and Carles Puig, for their patience and guidance throughout the project and Francesc Roure and Miquel Ferrer for their help in the mechanical analyses of the chariot and their help with Ansys respectively. I also want to thank Daniel Toledano for his assessment with the CAD design of the chariot, for his comprehension and his time.

To Sabah Abd El Razik Saddik, General Director at the Egyptian Museum, for her time and her advice on how to contact the Grand Egyptian Museum to see the chariots personally. Also, to Shreen Amin who was kind enough to present the General Director to me.

I am most grateful to the Grand Egyptian Museum for allowing me to enter the Wood Conservation Center, where the chariots were being restored. To Basma Yosaf for her mediation with the General Director of the Grand Egyptian Museum, Doctor Tarek Tawfik, and her attention during the visit. To Doctor Tarek Tawfik for allowing me to enter the Conservation Center. Also, I would like to thank Mohamed Moustafa, conservator at the Wood Laboratory, for his time and his explanations during the visit and for his attention to my questions.

Finally, thank you to my friends and family. To my friend Maria, you have been an invaluable companion all these years of study. To my mother, father and grandmother, for always being supportive and for believing in me in every step of the way. And for always accompanying me, no matter how far I need to go. You are my biggest support and inspiration, my anchors. Thank you for your patience, your guidance and your unconditional love.

Bibliography

Bibliographic References

Chondros, T. G., Milidonis, K. F., Rossi, C., & Zrnic, N. (2016). The Evolution of the Double-horse Chariots From the Bronze Age to the Hellenistic Times. *FME Transactions, 44, No 2,* 229-236.

Cloak, F. T. (1968). Cultural Darwinism: Natural Selection of The Spoked Wood Wheel. *Annual Meeting of the American Anthropological Association.* Seattle.

Kretschmann, D. E. (2010). Mechanical Properties of Wood. In R. J. Ross, *Wood handbook. Wood as an engineering material* (pp. 5.1-5.46). Forest Products Laboratory. USDA Forest Service.

Littauer, M., & Crouwel, J. (1985). *Chariots and Related Equipment from the Tomb of Tut'ankhamun.* Oxford: Griffith Institute.

Nietzsche, F. (1872). *The Birth of Tragedy*. E. W. Fritzsch.

Rovetta, A., Nasry, I., & Helimi, A. (2000). The chariots of the Egyptian Pharaoh Tut Ankh Amun in 1337 B.C.: kinematics and dynamics. *Mechanism and Machine Theory, 35*(7), 1013-1031.

Sandor, B. I. (2004, June 2). The Rise and Decline of the Tutankhamun-class Chariot. *Oxford Journal of Archaeology, 23*(2), 153-175.

Sandor, B. I. (2012). Chariots' Inner Dynamics: Springs and Rotational Inertias. En A. J. Veldmeijer, & S. Ikram (Ed.), *Chasing Chariots. Proceedings of the First International Chariot Conference* (págs. 217-228). Cairo: Leiden: Sidestone Press.

Sandor, B. I. (2012). The genesis and performance characteristics of Roman chariots. *Journal of Roman Archaeology, 25,* 475-485.

Tsoumis, G. (1991). *Science and Technology of Wood: Structure, Properties, Utilization.* New York: Van Nostrand Reinhold.

Other Bibliographic References

Abe, M. (2009). *Vehicle handling dynamics: theory and application.* Amsterdam: Elsevier Ltd.

Childe, V. G. (1954). Wheeled Vehicles. In C. Singer, E. J. Holmyard, & A. R. Hall (Eds.), *A History* *of Technology* (Vol. I: From Early Times to Fall of Ancient Empires, pp. 716-729). Oxford: Oxford University Press.

Dixit, U. S. (2017). Landmark Revolutionary Inventions in Mechanical Engineering. In U. S. Dixit, M. Hazarika, & J. P. Davim, *A Brief History of Mechanical Engineering* (pp. 15-46). Springer International Publishing.

Genta, G. (1997). *Motor Vehicle Dynamics: Modeling and Simulation.* Singapore: World Scientific.

Gillespie, T. D. (1992). *Fundamentals of vehicle dynamics.* Warrendale: Society of Automotive Engineers.

Heisler, H. (2002). *Advanced vehicle technology* (2nd ed.). Oxford: Butterworth-Heinemann.

Hoffmeier, J. K. (1976). Observations on the Evolving Chariot Wheel in the 18th Dynasty. *Journal of American Research Center in Egypt, 13*, 43-45.

Jazar, R. N. (2017). *Vehicle Dynamics: Theory and Application.* Springer International Publishing.

Kottas, D. (2012). *Madera: Arquitectura y construcción.* LinksBooks.

Lemaitre, J. (2001). *Handbook of Materials Behavior Models.* San Diego: Academic Press.

Lopez, F. (s.f.). *egiptologia.org*. Obtenido de Las Matemáticas en el Antiguo Egipto: Unidades, Pesos y Medidas: http://www.egiptologia.org/ciencia/matematicas/unidades.htm (last visited 2018/09/07)

Museum, T. B. (n.d.). *The British Museum: The Rhind Mathematical Papyrus*. Retrieved from http://www.britishmuseum.org/research/collection_online/collection_object_details.aspx?objectId=117389&partId=1 (last visited 2018/09/07)

Parraga, J. (1979). *Automoción 1.* Madrid: Ediciones Castillo.

Robinson, A. (1995). La lectura de la piedra Rosetta. In A. Robinson, *Historia de la escritura* (pp. 20-35). Thames and Hudson.

Robinson, A. (1995). Los jeroglíficos egipcios. In A. Robinson, *Historia de la escritura* (J. Pardo, Trans., pp. 92-107). London: Thames and Hudson.

Rodriguez, A. S. (2000). *Astronomia y Matemáticas en el Antiguo Egipto.* Aldebarán.

Roesler, J., Harders, H., & Baeker, M. (2007). *Mechanical Behaviour of Engineering Materials: Metals, Ceramics, Polymers and Composites.* New York: Springer-Verlag.

Ross, R. J. (2010). Moisture Relations and Physical Properties of Wood. En *Wood handbook : wood as an engineering material* (págs. 4.1-4.19). Forest Products Laboratory. USDA Forest Service.

Rousseau, J.-J. (1762). *The Social Contract* (Vol. 3). Amsterdam.

Rovetta, A., Nasry, I., & Helimi, A. (2000). The chariots of the Egyptian Pharaoh Tut Ankh Amun in 1337 B.C.: kinematics and dynamics. *Mechanism and Machine Theory, 35*(7), 1013-1031.

Roylance, D. (2008). *Mechanical Properties of Materials.* MIT.

Schramm, D., Hiller, M., & Bardini, R. (2014). *Vehicle Dynamics: Modeling and Simulation.* Berlin: Springer-Verlag.

Shaw, I., & Nicholson, P. T. (2000). *Ancient Egyptian Materials and Technology.* Cambridge University Press.

Taghavifar, H., & Mardani, A. (2017). *Off-road Vehicle Dynamics: Analysis, Modelling and Optimization* (Vol. 70). Switzerland: Springer International Publishing.

Uriel, P. F. (1994). Kadesh. El problema continuado. *Espacio, Tiempo y Forma, Serie II, Hª Antigua, t.7*, 429-451.

Wilford, J. N. (1994, February 22). Remaking the Wheel: Evolution of the Chariot. *The New York Times*, p. c1.

Wong, J. Y. (2008). *Theory of ground vehicles* (4th ed.). Hoboken: Wiley.